Effects of Periodized versus Non-Periodized Stretch Training Programs on Morphological Flexibility Adaptations and Muscle Performance in Artistic Gymnasts

by

© Camila de Paula de Lima

A thesis submitted to the

School of Graduate Studies

In partial fulfillment of the requirements for the degree of

Master of Kinesiology

School of Human Kinetics and Recreation

Memorial University of Newfoundland

June 20, 2018

St. John's, Newfoundland and Labrador

Abstract

Static Stretching (SS) is a popular technique performed to increase joint range of motion (ROM). Therefore, increases in joint ROM after long-term SS programs may be attributed to morphological adaptations. Periodized program have been adopted to induce greater adaptations to the neuromuscular system while avoiding overtraining effects. However, the effects of periodized stretch training interventions to investigate long-term stretching adaptations are still unknown. Therefore, the objective of this study was to compare the effects of a periodized (PD) and non-periodized (NP) programs on flexibility, hamstrings stiffness and muscle performance. Fifteen participants were allocated to either PD or NP SS training programs and tested pre- and post- 8 weeks for jump height, hip flexors, hip extensors and dorsiflexors range of motion (ROM), hamstrings stiffness and hamstrings and quadriceps peak torque (PT). The results demonstrated that both PD and NP stretch training programs similarly increased joint flexibility, hamstrings PT and jump height, and decreased hamstrings stiffness. However, PD elicited overall greater flexibility compared to the NP. Therefore, 8-week PD and NP SS programs can cause morphological adaptations to young gymnasts and increases in muscle performance. However, effect sizes indicate that longer PD stretch training was more advantageous for increasing flexibility and improving muscle performance.

ACKNOWLEDGEMENTS

I would like to thank my supervisor Dr. David G. Behm for his support over my master's degree. I also appreciate all the opportunities he has provided me, such as the possibility of attending to conferences and meeting well known researchers in our field.

I would like to express all my love to my family that has always supported me and loved me over my entire life. Without their love I would not be able to follow my dreams and work with such resilience and strength.

To my boyfriend, Cassio Victora Ruas as well, that even distant helped me to achieve all of my goals, listened and helped me in the hardest moments of my life.

To my friends Vicente, Marco, Rafinha, Julia, Marcos, Amanda, Luisa and Manuela who have always been the best friends of my life, that stayed by my side during my happiest moments and have always seen my brightness.

To my roommate Elena Jaimes, who shared with me different moments of my life in St. John's, and also to my colleagues Yimeng Li and Jonathan Low, who shared laughs and stories with me during the projects that we have collected data for.

I would also like to thank Dr. Tim Alkani for his kind heart and empathy that has never stopped him from helping any graduate student during their data collection.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
cm	Centimeter
EMG	Electromyography
ROM	Range of Motion
SD	Standard Deviation
SS	Static Stretching
PD	Periodized group
NP	Non-periodized group
PT	Peak torque
CMJ	Countermovement jump

Chapter 1: Review of Literature

1.1 Abstract

Stretching is a technique to improve range of motion (ROM). It has been consistently shown that static (SS), ballistic (BS) and dynamic (DS) stretching increase ROM. However, these ROM improvements are counterbalanced by research demonstrating decreased muscle performance mainly after SS. BS and DS typically induce either increased or no change in muscle force and power. However, there are conflicting descriptions in the literature regarding differences between BS and DS stretching, and thus further conflict regarding their specific effects on performance. One mechanism responsible for acute stretching increases on ROM may be decreased spinal excitability. Neurological changes associated with increased ROM may also be a major factor explaining static stretch-induced muscle performance decrements. However, when stretching is performed over a long term training program, flexibility increases may be attributed more to stretch tolerance. There are many factors involved in acute stretching responses on muscle performance such as duration, population, volume and muscles stretched. The population used in most stretching studies are usually not familiarized and do not regularly perform stretching, demonstrating low levels of flexibility. Additionally, the majority of studies including stretch training programs do not perform any type of stretching periodization program, with progressions involving changes on load, stretching mode and volume throughout the program. The lack of control for these variables in stretching training programs may lead to misleading information regarding acute and chronic stretching effect on muscle performance.

1.2 Introduction

SS, BS and DS stretching are widely used to increase joint ROM [1-5]. SS involves lengthening the muscle to a specific point and holding it for a period of time (i.e. 15-60 seconds)[2]. SS is a common technique for athletes, with some evidence that it provides either similar [1, 6] or greater ROM increases when compared to BS and DS [7-9]. While DS involves active movements through a full or nearly full ROM [10-12], BS is a technique that involves bouncing movements at the end of ROM [1, 12]. However, many studies have shown that although SS improves ROM, prolonged SS can acutely impair muscle performance [1, 2, 4, 5]. Therefore, many athletic populations have replaced SS with DS and BS in their training sessions.

DS seems to be an acceptable technique to be added to the training session of a population that does not have extensive or extreme levels of flexibility as their main training goal. Since DS consists of similar movements that will be performed during the athletes' performance, it adheres to the concept of training specificity [2]. The literature has demonstrated positive and null effects with DS on power and force performances [2, 3, 11, 13, 14], while a few studies have shown decreases in muscle performance [15, 16].

BS stretching is a less popular stretching technique because some studies have claimed a greater risk of injuries due to a very fast lengthening movement of the muscle [7]. However, Wyon et al. 2010 showed that BS can only increase the risk of injury when performed by a population that is not familiarized with the technique [17]. Opplert et al. 2017 showed that some acute stretching studies have used the DS terminology when referring to BS. The misconception between DS and BS differentiation leads to misinterpretation of the effects of both on muscle performance. Some studies have reported that BS leads to similar ROM improvements compared to SS, as well as similar results on muscle force [1, 18]. However, they differ on fatigue performance and between population with different levels of flexibility [1]. Lima et al. (2016) showed that BS stretching increased ballerinas' muscle resistance to fatigue. However, the acute stretching effects seem to be dependent on a variety and complexity of variables such as duration, volume, muscle and population [5, 19]. Most acute studies demonstrated stretching effects on populations that were not well familiarized with these techniques. There are many studies showing high reliability and external validity of research designs that had participants who were well familiarized or had a high level of experience in specific tasks that were used for testing [20-22]. Additionally, populations tested on these studies have little interest in increasing their ROM as their main training goal. This contrasts with populations such as gymnasts, dancers, figure skaters and others that are submitted to extensive and intensive stretching programs since early ages. There have been very few studies in the literature showing the acute effects of stretching in a very flexible population such as gymnasts, ballerinas, and figure skaters.

Many of the studies showing acute effects of prolonged SS show similar results on ROM increases and muscle force impairments. However, only a few studies have investigated stretch training effects on ROM, where flexibility enhancement has been addressed to either morphological, neurological or psychological changes [23]. The morphological changes are measured by examining changes in muscle tendon stiffness, muscle fascicle length and pennation angle [24, 25]. However, a recent review performed by Freitas et al. [23] showed that most of the studies involving short periods of stretch training could not support the increase of ROM as a morphological change. Previous studies have suggested that neural adaptations are responsible for acute and early adaptations to stretching programs [26, 27]. Longer periods of stretch training programs showing flexibility gains may be underlined by changes in stretch tolerance [28]. There are many studies showing decreases in spinal excitability using a variety of techniques [26, 29-31]. However, this could also be neutralized by supraspinal or corticospinal excitability, thus compensating these decreases found in the spinal excitability.

However, the neurological changes found in stretch training programs occurred only with a short period of stretching training (< 4 weeks) [32].

The research community still seems to widely accept the increase in stretch tolerance as the main mechanism for flexibility gains from a stretch training program. Magnusson et al. 1996 showed that short stretch training periods (3 weeks) increases participants stretch tolerance with no changes found on muscle tendon stiffness. However, the stretch training programs used by the majority of the chronic studies lack periodization and do not modulate volume, load and mode of stretching. Many studies have shown positive results on strength and power gains after a periodized strength training program over a non-periodized program [33-37]. The modulation of volume and intensity of strength training during periodization allow for appropriate overcompensation of strength. Perhaps, modulation of stretch training variables would accomplish similar goals by providing greater flexibility overload adaptations (gains). Additionally, most of the population, including gymnasts, have been using similar stretching programs for years with little modification in their programs. Thus, there is a lack of different stimuli to generate greater physiological adaptations. This may be a hypothesis why most studies have only found changes in stretch tolerance rather than neurological or morphological changes.

1.3 Acute Effects of Stretching

Stretching is a technique that involves lengthening musculotendinous and other elastic structures under static or dynamic conditions, usually for short periods of time, thus enhancing joint flexibility (Joke, Nelson Arnold et al. 2007[2, 4, 5]). SS is one of the most popular types of stretching performed within athletic and non-athletic populations. It consists of lengthening the muscle to the end of ROM to near or maximal point of discomfort and holding this position for an extended period of time (i.e. 15-60 seconds)[2, 4]. It has been incorporated as a warm up for exercise routines to improve muscle performance and reduce the risk of injuries [7, 38]. However, a consistent body of research in this field has shown that longer periods of static stretching (>60s) may cause impairments of muscle performance, such as the maximal force output, explosive force, power, balance, reaction and movement time in untrained or recreationally active populations [4, 5, 9, 39]. Therefore, BS and DS stretching have been reported to lead to less impairments on muscle performance and similar ROM improvements as SS in some studies [1, 6]. However, SS has been reported to provide greater ROM than DS or BS in a number of studies [7-9]. There is some misunderstanding in the literature regarding the differences between both stretching techniques [12]. While BS involves lengthening the muscle to the maximal point of discomfort and performing bouncing movements at the final angles of the joint ROM ([1, 12]), DS involves the performance of a controlled movement through the ROM of the active joint(s) [5]. The dynamic nature of DS with the reported lack of subsequent performance impairments has led to a paradigm change in the last 10-20 years where DS is emphasized to a greater degree than SS as a predominant warm up technique to prepare for an upcoming exercise. Although some studies have shown similar increases in ROM for SS, BS and DS [1, 6, 7], typically only trivial to small changes or increases in muscle power after BS and DS have been found (Behm et al. 2016).

However, a few studies have shown performance decreases after DS and BS [9, 14, 18]. Behm et al. (2016) reviewed 184 studies showing a decrease in squat power performance after DS stretching. Therefore, they suggested that these impairments happened due to the lack of specificity between the task and the DS stretching exercises. Stretching effects probably depend on a complex combination of factors such as participants with different sporting backgrounds [1, 19] , stretch intensity, volume, type, structure, progression and control [5]. All these variables can cause specific acute and chronic effects on muscle performance. Fletcher et al. 2010 examined 2 sets of 10 repetitions of slow vs fast DS on both countermovement jump (CMJ) and drop jump (DJ) jump heights in recreationally college athletes. They found that performing fast DS led to greater increases of CMJ and DJ performance and both stretching velocities led to 9.07%, 7.67%, 11.78% and 13.27% increases of knee ROM during CMJ and DJ, respectively. However, the dynamic stretching exercises used in this research protocol seemed to be more focused on preparing the participants for the following exercises that they will be performing in their routines than on increasing ROM. Nevertheless, Unick et al. (2005) found no changes of vertical jump height scores after three sets of 15 seconds of four SS and BL stretching exercises for gastrocnemius, hamstrings and quadriceps muscles in resistance trained women.

Behm et al. (2016), in a comprehensive literature review that included more than 200 articles, demonstrated that SS performed for long periods of time negatively impacts force production and power. Therefore, a plethora of research evidence have identified negative effects of SS on muscle performance, thus influencing coaches to reorganize exercise routines of athletes avoiding the inclusion of this stretching technique [4, 25, 40]. Another systematic review by Kay et al. (2012) showed strength impairments from SS following longer periods (>45s) of SS. However, some studies have shown similarities in strength decrements between SS and BS. Lima et al. (2016) found similar decrements in hamstrings peak torque after more than 60 s of BS and SS stretching. Wallmann, Christensen, Perry, Hoover [41] compared the effects of SS, DS and BS on 40 yard sprint performance of runners. They found a similar increase in the performance time of runners. However, there is some evidence showing increases in ROM, power and strength after SS. Shrier [42] in a review of 23 studies regarding the SS effects on performance showed that SS improved force, speed and power. However, they did not provide information regarding the SS duration. Regardless of the few studies that have provided information regarding SS-induced improvements on performance, it seems to be well established that prolonged periods of SS decreases muscle performance of recreationally trained populations [4, 5].

The majority of studies mentioned in this literature review may have a population bias. Whereas most studies use college aged recreationally active populations, few studies have examined populations that are interested in stretching to achieve high levels of flexibility and ability to perform sport specific exercises. The acute negative effects from stretching may differ when performed by a highly flexible population [1]. Morrin, Redding [43] found no SS impairments of balance, vertical jump and ROM in dancers. They also concluded that combining SS and DS can enhance performances of jump height and balance. Fletcher [11] and Lima et al. (2016) also found similar ROM increases and decreases on hamstrings peak torque after BS and SS for both ballet dancers and resistance trained women [44]. Additionally, a review on different stretching techniques for dancers showed that the emphasis of DS is to prepare the joints and elastic tissues for the exercises that will be performed during their routines [17]. It also often includes the same exercises performed during an athletic routine and it is thought to cause an increase of muscle and body temperature [3]. BS is usually recommended for advanced dancers since it can help them to achieve extreme levels of muscle length [17], however coaches may feel more comfortable in prescribing DS to their athletes, as BS may increase the risk of injury such a muscle strain [7]. Although prolonged SS can cause acute muscle performance impairments in populations that do not stretch very often it may still be one of the superior techniques to improve flexibility in populations that stretch on a daily basis [8, 45].

Nevertheless, for some sports, flexibility may not be the main training focus as the general training aim is to achieve high levels of force, power and endurance. In these cases, it may be more suitable performing a dynamic warm up rather than SS exercises [13]. However, the literature seems to not focus on sporting populations that start stretching at a very young age and perform high levels of stretch training to attain flexibility demands needed in practice and competition, such as gymnasts, ballet dancers, figure skaters, among others. Coaches select and classify their athletes for competitions based on many factors that are related to their anthropometric data, performance and psychological aspects [46-48]. However, some specific sports athletes can be selected to represent their institution or progress to a higher category according to their level of flexibility [47]. Performing only DS or simple stretching exercises during warm up routines may not be sufficient to achieve their desired levels of flexibility.

According to the concept of training specificity, strength and power training generate the greatest improvements when training is specific to the tasks performed in the sport or activity (Behm and Sale 1993; [49]. For instance, Allison, Bailey, Folland [50] investigated the effects of prolonged static stretching on running economy and neuromuscular function in male runners. They found that maximal oxygen consumption values were not affected during the running tasks after eight stretching exercises of 40 seconds for quadriceps, hamstrings and plantar flexors. However, SS decreased isometric maximal voluntary contraction (5.5%) and CMJ (5.6%), respectively. The reason for these results may be because maximal oxygen consumption test is more specific to runners' performance than isometric maximal voluntary contraction test. In contrast, [51] showed that general populations with either low or high flexibility levels decreased hamstrings peak torque after stretching. However, the population that had high flexibility returned to the baseline peak torque levels faster than the population with low flexibility. Behm, Bradbury, Haynes, Hodder, Leonard, Paddock [52] also investigated a short period of SS (3x30 seconds) in 9 males and 9 females. They did not find any correlation between changes in ROM and stretch impairments of CMJ, DJ and quadriceps and hamstrings MVC's. They also performed a short period of SS training (4 weeks 5 days per week) for quadriceps, hamstrings and gastrocnemius in 12 males not engaged in flexibility training. Participants performed the same SS volume as the acute study (3x30 seconds) and were similarly tested. The magnitude of stretching impairments on muscle performance remained the same even after the short stretching training protocol. The authors concluded that flexibility is not correlated to stretch-induced impairments. However, the stretching training protocol was performed for a short period (4 weeks), and previous studies have shown that this training period is insufficient to induce morphological changes [23]. Lima et al. (2016) also found that ballerinas, who are highly flexible, after performing BL stretching had greater endurance thus inducing less fatigue, which shows that task specificity seems to play a major role in the stretching responses.

There are some conflicts in the literature regarding effects and definition of DS and BS stretching [12]. DS stretching is a technique more focused on developing athlete's performance for their daily routines than focusing on BS. The majority of the studies have shown positive or no changes on the acute effects of DS [8, 11, 14]. However, in the Behm et al. (2016) review, there were a few DS studies demonstrating some impairments in power. Therefore, the literature shows some contradictory results of the acute effects from stretching on functional performance, which seems to be highly dependent on the flexibility levels and specific training/activity performed by different populations. Nevertheless, to date no thorough investigation has been performed exploring neurophysiological and morphological aspects underpinning stretching effects on muscle and functional performance between populations with high vs. low levels of flexibility.

1.4 Volume, Intensity and Duration of Stretching

The major variables underlying stretching effects are intensity, duration, frequency and volume. In a review study, Behm et al. (2016) concluded that these variables have a direct impact on the acute stretching effects. However, Bandy et al. (1998) compared the effects of static stretching on hamstrings flexibility using different strategies, which involved stretching for 30 seconds vs 60 seconds, and one time per day vs three times per day, and found that managing either volume or frequency led to similar results for increasing hamstrings ROM. In agreement with these results, Ogura, Miyahara, Naito, Katamoto, Aoki [53] found similar increases for hamstrings ROM between 30 vs 60 seconds of SS. However, they also reported a decrease of hamstrings maximal voluntary contraction (MVC) after 60 seconds of SS, although 30 seconds of SS did not impair hamstrings MVC. The literature seems to consistently agree that prolonged SS acutely causes some decrements on muscle performance for general population [4, 5, 39]. However, stretching protocols utilized in the aforementioned studies appear to not rely on the athletic training programs or exercises from the general populations tested. Additionally, stretching volume and frequency used in different study protocols seem to be low compared to what athletes with high flexibility levels (e.g. gymnasts and dancers) usually perform.

Another factor that may influence the stretching effects is the intensity. The most common protocol to measure stretching intensity is a discomfort scale [54]. Participants are usually asked to perform stretching exercises at their maximal point of discomfort or mid-point of discomfort. Freitas et al. (2015) found greater decreases of hamstring passive torque after a combination of long duration of 180 seconds of passive stretching and low intensity that was classified at the mid-point of discomfort (50% of their maximal). A decrease of passive torque is highly correlated to greater muscle-joint compliance which leads to increases of ROM. Freitas, Vaz, Bruno, Andrade, Mil-Homens [55], in a second study, examined the effects of high intensity-moderate duration vs low intensity-long duration hamstrings passive stretching with university students. The high intensity-moderate duration protocol consisted of stretching at their maximal point of discomfort for 90s without rest and the low intensity-long duration was performed by stretching at their mid-point of discomfort for 900 seconds. The high intensity – moderate duration protocol induced an increase in hamstrings peak passive torque where the low intensity-long duration did not demonstrate any increases of passive torque after an hour of passive stretching. However, after one minute of stretching the hamstrings muscles, passive torque decreased to a greater extent after low intensity-long duration protocol compared to high intensity- moderate duration. The authors suggested that duration may play a greater role than intensity, but that increases of hamstrings passive torque after the high intensity-moderate duration protocol may have occurred due to an increase of stretch tolerance. Additionally, the authors reported that duration may play a greater role on ROM and passive torque changes when stretching is performed at the mid-point of discomfort, as it seems to be more efficient than stretching at the maximal point of discomfort. Behm, Kibele [56] investigated the effects of three different stretching intensities (100%, 75% and 50% of point of discomfort) on CMJ, DJ and SJ in university students. The SS protocol consisted of four sets of 30 seconds for quadriceps, hamstrings and plantar flexors. The different intensities (mid, submaximal and maximal point of discomfort) affected DJ, SJ and CMJ height by 4.6%, 5.7%, 5.4%, respectively. They also found that stretching decreased CMJ by 3.7% when CMJ was performed using the preferred knee flexion strategy, but it decreased CMJ by 3.8% when CMJ was performed using very short knee flexion amplitude. However, they did not investigate ROM. These studies demonstrate that using stretching intensity at mid-point of discomfort may be a better strategy to use to increase ROM and to diminish power performance impairments. High intensity stretching appears not to lead to high magnitude changes in passive muscle stiffness and ROM. Young, Elias, Power [57] examined the effects of a combination of running and static stretching of four different durations and two intensities with dancers. Running + SS was performed at their maximal point of discomfort for the subsequent durations: one min of SS, two minutes of SS and four minutes of SS. The fourth condition was performed as 2 min of SS at 90% of their maximal point of discomfort. They concluded that none of the different stretching intensities and durations changed their ROM. However, running + four minutes of stretching led to greater impairments on DJ jump height, whereas running + two minutes of stretching at 90% did not cause any impairments on DJ performance. This study is in agreement with past studies that stretching at the maximal point of discomfort may not be the most advantageous strategy to increase muscle performance [58, 59]. It is important to point out that these variables are extremely important for improving flexibility and influences on force, power and technical sport movements. In comparison to strength and power training programs, which are progressive and modulate training variables (i.e. intensity, volume, load) throughout their duration, flexibility training tends to remain fairly static over time in terms of types of exercises, intensities and durations.

1.5 Periodization of Training

To optimize the effect of strength and power training stressors on neuromuscular overcompensatory training adaptations, periodized training programs for strength, power, and endurance (muscle aerobic and anaerobic) have been almost universally adopted [36, 60]. There are many types of periodization models such as traditional, undulating model, repeated mesocycle and others (Brown et al. 2005). Traditional periodization has a main goal to optimize peak performance manipulating a progressive load and training cycles while avoiding overtraining effects. Overtraining effects lead to a decrease in performance as an early effect and after long periods of overtraining there is a mental and muscular fatigue combined effect that may lead to injuries performance impairments. Brown et al. 2005 defined three phases that occur with the periodized training. Phase I can be defined as an "alarm phase" which occurs in the early period of the training and leads to more neurological adaptations. With Phase II, there is a "super compensation" where the adaptations are the result of a variety of physiological changes [36]. These changes can be related to changes in hormones, motoneurones firing rate and recruitment, increases in muscle size and others [61, 62]. If the training progression continues, the individual will finally achieve their training goal and be able to have their maximal performance and morphological changes. However, the last phase that is defined as (maladaptation) may occur when the increases and the progression continuous to happen for a longer period than necessary and the individual finally reaches the overtraining stage [36]. This important evidence on periodization training has been used largely for the research and practitioner's community in the strength and conditioning field, thus, providing significant improvements for the athletic and non – athletic population performance.

There are some studies showing differences between traditional/linear periodization versus undulating model [33, 63]. The undulating model consists of manipulating more frequently the training volume and load in order to allow the neuromuscular system longer periods of recovery during the use of lighter loads [37].

Additionally, there are greater stimuli to the neuromuscular system through the manipulation of training variables such as power, strength, velocity and others [37].

Some studies have shown the combination or variation between strength and power variables on increases in muscle performance. Lamas, Ugrinowitsch, Rodacki, Pereira, Mattos, Kohn, Tricoli [64] investigated the effects of 8 weeks of power versus strength training on jump and strength performances in physically active men. They found that for MVC and SJ there were similar increases between power and strength training. However, CMJ height was only increased after power training with no changes for the strength training group. This may show that for movements consisting of more general muscles and tasks, non-specific training leads to increases in specific tasks. However, tasks that include a higher movement complexity, muscles activation, coordination and cognitive attention may need more specific training to generate greater improvements [49]. Behm, Young, Whitten, Reid, Quigley, Low, Li, Lima, Hodgson, Chaouachi [49] in a comprehensive review on the effects of strength versus power training on muscle strength, power and speed in youth, showed that jump performances were generally higher after specific power training. However, no changes were found after strength training. Although, jump performance was increased after specific power training, sprint performance was greater after strength training. The authors concluded that strength training may be better used for youth during the initial phase of training to result in a greater strength foundation to power performances. However, all periodization and specificity effects have been shown only in resistance, power and aerobic training variables. Therefore, it remains unknown if stretching periodization is also effective on maximizing chronic adaptations to stretching.

Most gymnasts have performed the same type and volume of stretching exercises throughout years of their training life. However, from our knowledge there are no studies showing whether the performance of the same stretch training with no increases in volume or load are effective in increasing flexibility. It is well known that periodization for strength training is necessary to cause greater musculotendinous and neural adaptations to increase muscle force output [36, 61, 62]. This may be the case for stretching programs as well, it is also well documented that many gymnasts drop out from gymnastics due to a very high level of mental and muscular fatigue, and many times for being exposed to stretching exercises to an extreme level of intensity, volume and frequency [65-67]. A factor that may play a role in the high rate of drop outs could be related to the unchanged stretch training programs. Nevertheless, more research is needed to evaluate the effects of progression and periodization of stretch training on muscle performance, as well as on improving adherence and motivation to the sport/activity. Greater degrees of ROM may be achieved over a periodization program due to the longer recovery periods. This may cause increases in muscle length which can cause more effective stretch shortening cycle and muscle force.

1.6 Mechanisms Underlying Stretching

The literature is still not conclusive regarding mechanisms underpinning stretching effects on muscle performance and ROM. The capability to achieve and maintain extensive levels of flexibility has been related to changes in either morphological, neurological, or psychological (stretch tolerance) factors [23, 27, 28, 55]. The neurological changes after stretching persist for only short periods, which may be characterized as an acute response [27, 30, 31, 68]. Morphological changes are predominately related to longer term flexibility training, leading to chronic changes of tissue properties, such as muscle thickness, pennation angle, fascia stiffness, and muscle-tendon stiffness [69, 70]. However, the alteration in stretch tolerance itself may not fully explain the capacity of ballerinas, gymnasts, and other flexibility reliant athletes to achieve high levels of ROM even when they are not training.

1.6.1 Acute Mechanisms

Acute passive stretching involves changes in the sensitivity of primary afferent nerves that innervate nuclear bag and nuclear chain fibers [26, 68]. Both fibers are sensitive to changes of muscle length and rate. Stretching these muscle fibers will increase sensitivity and firing rate since there will be a change on muscle length and rate, respectively, in the beginning of the stretching exercise. Therefore, as the duration of static-passive stretching increases, the fibers accommodate to this new length, and changes of rate no longer occur, leading to a new set position of the muscle as a new baseline. This demonstrates that there are possible decreases in Ia afferent pre-synaptic input after passive stretching [26, 27].

It seems to be well established in the literature that stretching the muscle (passive lengthening) induces depression of Hoffman (H-) reflex amplitude, thus increasing pre-synaptic inhibition. This increase in the pre-synaptic inhibition have been related to a decrease in spinal excitability [26, 29-32, 68]. However, some studies argue that measuring H-reflex amplitude may not be sufficient to conclude that there is a decrease in spinal excitability since there are more pathways involved. The depression of H-reflex amplitude can be measured through a decrease in the response of Ia afferent pre-synaptically or a decrease in motoneurone excitability. In addition, a few studies have shown the effects of stretching on corticospinal excitability, which may compensate for the decreases in spinal excitability [71, 72]. However, this was not supported by [71, 73], who found a decrease in cortical motor output during muscle lengthening and demonstrated that there is an acute decrease in cortical and spinal excitability after muscle lengthening. There is insufficient research to support potential changes in the entire neurophysiological pathway.

1.6.2 Population Specific Adaptations

1.6.3 High Flexibility Populations (*Dancers, Gymnasts and Figure Skaters)*

Most studies use college aged, recreationally active populations, few studies have examined populations that are interested in stretching to achieve high levels of flexibility and ability to perform sport specific exercises. However, the acute negative effects from stretching may differ when performed by a highly flexible population [1]. Morrin et al. found no SS impairments on balance, vertical jump and ROM variables in dancers. They concluded that combining SS and DS can enhance performances of jump height and balance[43]. Fletcher [11] and Lima et al. also found similar ROM increases and hamstrings peak torque decreases after BS and SS for both ballet dancers and resistance trained women [44]. Additionally, a review of different stretching techniques for dancers showed that the emphasis of DS is to prepare the joints and elastic tissues for the following exercises that will be performed during their routines [17]. It also often includes the same exercises performed during athletic routine and it can increase muscle and core (body) temperature [3]. BS is usually recommended for advanced dancers since it can help them to achieve extreme levels of ROM [17], however coaches may feel more comfortable in prescribing DS to their athletes, as BS may increase the risk of injuries such as muscle strains [7]. Although prolonged SS can cause acute muscle performance impairments in populations that do not stretch very often it may still be one of the superior techniques to improve flexibility in populations that stretch on a daily basis [8, 45]. More research is needed to examine the SS and DS dose response relationship of high flexible athletes compared to the average population in terms of ROM and possible subsequent performance impairments. However, as a reminder, there are no studies showing performance impairments when stretching is incorporated into a full warm-up[3, 5, 74, 75].

1.6.4 Recreationally and Strength Trained Athletes

For some sports, flexibility may not be the main training focus as the main training aim is to achieve high levels of force, power and endurance. In these cases, it may be more suitable to perform a dynamic warm up rather than SS exercises [13]. According to the concept of training specificity, strength and power training generate the greatest improvements when training is specific to the tasks performed in the sport or activity [76 49]. For instance, Allison et al. investigated the effects of prolonged static stretching on running economy and neuromuscular function in male runners. They found that maximal oxygen consumption values were not affected during the running tasks after eight stretching exercises of 40 seconds each for quadriceps, hamstrings and plantar flexors[50]. However, SS decreased isometric maximal voluntary contraction and CMJ by 5.5% and 5.6%, respectively. The disparity with these results may be attributed to the task specificity of the maximal oxygen consumption test for runners' performance versus a non-specific isometric MVC test. In contrast, Babault et al. showed that general populations with either low or high flexibility levels decreased hamstrings peak torque after stretching[62]. However, the population that had high flexibility returned to the baseline peak torque levels faster than the population with low flexibility. Behm et al. also investigated a short period of SS (3x30 seconds) in 9 males and 9 females. They did not find any correlation between changes in ROM and stretch impairments of CMJ, DJ and quadriceps and hamstrings MVCs. They also performed a short period of SS training (4 weeks 5 days per week) for quadriceps, hamstrings and gastrocnemius in 12 males not engaged in flexibility training. Participants performed the same SS volume as the acute study (3x30 seconds) and were similarly tested. The magnitude of stretching impairments on muscle performance remained the same even after the short stretching training protocol. The authors concluded that the extent of flexibility is not correlated to stretch-induced impairments. However, the stretch training protocol was performed for a short period (4 weeks), and previous studies have shown that this training period is insufficient to induce morphological changes [23]. Lima et al. also found that ballerinas, who are highly flexible, after performing BS stretching had greater endurance thus inducing less fatigue, which shows that task specificity seems to play a major role in the stretching responses.

1.6.5 Chronic Mechanisms

The physiological mechanisms for ROM increases appear to differ between acute and chronic stretching. It seems to be well established that stretching programs of six to eight weeks or more lead to changes in ROM and muscle passive torque resistance [25, 40, 69]. The main physiological mechanism involved with flexibility increases after long term stretching interventions may be due to changes in muscle and fascicle length, muscle-tendon stiffness and muscle hardness. Muscle- tendon stiffness can be measured through a passive resistance applied to these structures while they are being stretched [28]. Changes in muscle-tendon stiffness can be explained by the length-tension relationship, which demonstrates that when a muscle is being shortened the tension applied is lower than when the muscle is elongated [28]. Decreases in the passive resistance from the muscle-tendon may happen because there is a loss of energy from the viscoelastic properties [77]. Muscle hardness can be defined as the mechanical properties of the muscle related to its viscoelasticity and stiffness. Okamura, Tsukune, Kobayashi, Fujie [78] investigated the effects of acute SS in muscle hypotonicity. They found that muscle viscoelasticity had greater decreases at the end of the stretching exercise compared to the start phase. Akagi, Takahashi [79] evaluated the effects of 5 weeks SS program consisting of 3 sets of 2 min SS of gastrocnemius for 6 days per week in males. They showed that a short stretching program led to a decrease in muscle hardness. However, a few short-term stretching studies did not find chronic effects of stretching in muscle stiffness, fascicle length and muscle-tendon junction stiffness [24, 80]. Contrary to these findings, Freitas et al. [70] found biceps femoris fascicle length and ROM increases after eight weeks of stretching training. In agreement with this study, Guissard, Duchateau [31] determined that the improvement of flexibility was correlated to a decrease in muscle passive stiffness after 10 sessions of stretching training. They also found that there was a decrease of H- and T- reflex, and that flexibility and passive stiffness were maintained for one month after training, but the reflexes returned to the baseline state. Nevertheless, they concluded that the main physiological mechanisms responsible for the long term stretching effects is the reduction in passive stiffness of muscle-tendon and decrease in the amplitude of H- and T-reflex. Therefore, the reflex responses could be one of the major mechanisms of gaining flexibility in short-time.

Changes in muscle-tendon may also be responsible for chronic adaptations from long-term stretching programs. Kokkonen, Nelson, Eldredge, Winchester [81] reported that after 8 weeks of stretching training there was an increase in 1RM knee extension and flexion, jump height and ROM. However, LaRoche, Lussier, Roy [82] did not find any differences of hip extensors peak torque and power from pre- to post- 4 weeks of BS and SS program, although they did not report the stretching intensity of the protocol. However, a recent review on the chronic stretching effects in the muscle-tendon properties has suggested that short term stretching (4 to 8 weeks of stretching program) has small effects on the resistance of passive torque, which suggests that muscle-tendon stiffness remains similar. They suggested that the absences of changes in muscle tendon structures may be due to three factors: lack of variability on intensity, volume and type of stretching; greater changes in non-muscular structures (such as: fascia) rather than muscle-tendon changes; and stretch tolerance. Therefore, research may still lack with advanced equipment to assess all possible changes in muscle and tendon structures that are caused by stretching.

It is well documented in the literature that periodization is important for strength training to alter muscle and tendon structures. However, stretching training programs are usually performed using the same stretching exercises with slight changes of intensity and volume. For instance, stretching training is constantly performed with a lack of any type of periodization for intensity, volume and frequency progressions in gymnasts, who start training from a very young age and perform stretching programs throughout their athletic life that involve very painful stretching exercises. Therefore, further research is needed on stretching training periodization, which may enable greater findings on the effects of stretching in morphological adaptations.

1.6.6 Stretch Tolerance

Modification of sensation after stretch training protocols appear not to have been evaluated after a long-term stretching program (more than 8 weeks). As previously mentioned Magnusson, Simonsen, Aagaard, Sørensen, Kjaer [24] concluded that modification of sensation is the main explanation for increases of flexibility, as they did not find increases of passive muscle stiffness. An additional study of Magnusson, Simonsen, Aagaard, Boesen, Johannsen, Kjaer [83] showed that acute static stretching decreased hamstrings stiffness similarly between participants that had low and normal levels of hamstrings flexibility. However, no changes were found in hamstrings cross sectional area. Participants that had tight hamstrings demonstrated lower peak torque and lower hamstrings stiffness during passive stretching compared to normal participants. However, [84] reported in a review on stretching techniques of passive properties changes that a single stretching exercise can induce a 30% decrease of hamstrings viscoelasticity. They also showed that more than one repetition of stretching may lead to a decrease in muscle stiffness, which may return to baseline levels after one hour. These morphological changes were found after acute stretching interventions. They also investigated hamstrings passive resistance and electromyography (EMG) after 3 weeks of SS. They concluded that no changes were found with the EMG signal and passive resistance, although stretching led to an increase of stretch tolerance. Thus, based on these results the authors suggested that changes in muscle extensibility are a result of stretch tolerance increases rather than morphological modifications. However, although stretching tolerance seemed to play a significant role for the increases of flexibility, this may not be the only possible explanation. For instance, stretch tolerance does not explain the fact that retired gymnasts that do not perform stretching exercises anymore are still able to perform exercises that involve high ROM.

1.7 Conclusions

The stretching literature demonstrates that the main physiological mechanism related to the acute effects of stretching on the increase of ROM are neurological rather than morphological or psychological aspects. The decrease in spinal excitability measured through a variety of techniques already mentioned in this review leads to decreased neuromuscular reflex activity thus increasing ROM. However, the effects from stretching on muscle performance may differ depending on the stretching mode. Although SS is one of the main stretching techniques to increase ROM, the majority of studies have shown a decrease in muscle force and power after long periods of SS. Nevertheless, BS and DS may lead to similar increases on ROM as SS, but demonstrated positive or neutral changes in muscle power. In addition, although, DS may be an effective technique to increase specific performance the literature is not very clear whether it can be considered a stretching technique or a warm up technique. All these responses seem to be directly related to variables that may change their output such as management of duration, volume, load, intensity, muscle and population.

The main physiological mechanism for the increase of flexibility after a chronic stretching program is changes on stretch tolerance. There were insufficient studies to support morphological or neurological changes after stretching program as the major factors. Stretch tolerance seems to increase and muscle tendon stiffness remains similar after 8 weeks of stretching. Although, stretch tolerance may play a major role in flexibility increases after stretching program, this may have been found because of the lack of periodization to elicit physiological stimulus during the stretching programs performed in the reviewed studies. Collectively, most studies that investigate stretch training responses on ROM and muscle performance used similar stretching modes, load and volume throughout the entire training. This may not have been enough to elicit greater morphological and neurological adaptations from stretching programs.

Further research is needed to investigate long term stretching programs effects on morphological adaptations and stretching tolerance. Additionally, manipulating stretch training variables such as intensity, type of stretching, frequency and volume in order to investigate mechanisms underpinning ROM improvements can lead to greater insights of morphological adaptations and improve practical applications of stretching training effects. Further research is needed to investigate the effects of periodization of long-term stretching training on morphological adaptations, such as muscle-tendon and non muscular structure modifications, in highly flexible population.

1.8 References

Aagaard, P. (2003). Training-induced changes in neural function. *Exercise and sport sciences reviews, 31*(2), 61-67.

Aguilar, A. J., DiStefano, L. J., Brown, C. N., Herman, D. C., Guskiewicz, K. M., & Padua, D. A. (2012). A dynamic warm-up model increases quadriceps strength and hamstring flexibility. *The Journal of Strength & Conditioning Research, 26*(4), 1130-1141.

Akagi, R., & Takahashi, H. (2014). Effect of a 5-week static stretching program on hardness of the gastrocnemius muscle. *Scandinavian journal of medicine & science in sports, 24*(6), 950-957.

Allison, S. J., Bailey, D. M., & Folland, J. P. (2008). Prolonged static stretching does not influence running economy despite changes in neuromuscular function. *Journal of sports sciences, 26*(14), 1489-1495.

Avela, J., Kyröläinen, H., & Komi, P. V. (1999). Altered reflex sensitivity after repeated and prolonged passive muscle stretching. *Journal of Applied Physiology, 86*(4), 1283-1291.

Ayala, F., de Baranda, P. S., Croix, M. D. S., & Santonja, F. (2012). Reproducibility and criterion-related validity of the sit and reach test and toe touch test for estimating hamstring flexibility in recreationally active young adults. *Physical Therapy in Sport, 13*(4), 219-226.

Babault, N., Bazine, W., Deley, G., Paizis, C., & Lattier, G. (2015). Direct relation of acute effects of static stretching on isokinetic torque production with initial flexibility level. *International journal of sports physiology and performance, 10*(1), 117-119.

Bacurau, R. F., Monteiro, G. A., Ugrinowitsch, C., Tricoli, V., Cabral, L. F., & Aoki, M. S. (2009). Acute effect of a ballistic and a static stretching exercise bout on flexibility and maximal strength. *J Strength Cond Res, 23*(1), 304-308. doi:10.1519/JSC.0b013e3181874d55

Bandy, W. D., Irion, J. M., & Briggler, M. (1998). The effect of static stretch and dynamic range of motion training on the flexibility of the hamstring muscles. *Journal of Orthopaedic & Sports Physical Therapy, 27*(4), 295-300.

Barroso, R., Tricoli, V., Santos Gil, S. D., Ugrinowitsch, C., & Roschel, H. (2012). Maximal strength, number of repetitions, and total volume are differently affected by static-, ballistic-, and proprioceptive neuromuscular facilitation stretching. *J Strength Cond Res, 26*(9), 2432-2437. doi:10.1519/JSC.0b013e31823f2b4d

Beedle, B., Rytter, S. J., Healy, R. C., & Ward, T. R. (2008). Pretesting static and dynamic stretching does not affect maximal strength. *The Journal of Strength & Conditioning Research, 22*(6), 1838-1843.

Behm, Young, J. D., Whitten, J. H., Reid, J. C., Quigley, P. J., Low, J., . . . Chaouachi, A. (2017). Effectiveness of Traditional Strength vs. Power Training on Muscle Strength, Power and Speed with Youth: A Systematic Review and Meta-Analysis. *Frontiers in physiology, 8*, 423.

Behm, D. G., Blazevich, A. J., Kay, A. D., & McHugh, M. (2015). Acute effects of muscle stretching on physical performance, range of motion, and injury incidence in healthy active individuals: a systematic review. *Applied physiology, nutrition, and metabolism, 41*(1), 1-11.

Behm, D. G., Blazevich, A. J., Kay, A. D., & McHugh, M. (2016). Acute effects of muscle stretching on physical performance, range of motion, and injury incidence in healthy active individuals: a systematic review. *Appl Physiol Nutr Metab, 41*(1), 1-11. doi:10.1139/apnm-2015-0235

Behm, D. G., Bradbury, E. E., Haynes, A. T., Hodder, J. N., Leonard, A. M., & Paddock, N. R. (2006). Flexibility is not related to stretch-induced deficits in force or power. *Journal of sports science & medicine, 5*(1), 33.

Behm, D. G., & Chaouachi, A. (2011). A review of the acute effects of static and dynamic stretching on performance. *European journal of applied physiology, 111*(11), 2633-2651.

Behm, D. G., & Kibele, A. (2007). Effects of differing intensities of static stretching on jump performance. *European journal of applied physiology, 101*(5), 587-594.

Behm, D. G., Peach, A., Maddigan, M., Aboodarda, S. J., DiSanto, M. C., Button, D. C., & Maffiuletti, N. A. (2013). Massage and stretching reduce spinal reflex excitability without affecting twitch contractile properties. *Journal of Electromyography and Kinesiology, 23*(5), 1215-1221.

Bompa, T., & Buzzichelli, C. (2015). *Periodization Training for Sports, 3E*: Human kinetics.

Bozic, P. R., Pazin, N. R., Berjan, B. B., Planic, N. M., & Cuk, I. D. (2010). Evaluation of the field tests of flexibility of the lower extremity: reliability and the concurrent and factorial validity. *The Journal of Strength & Conditioning Research, 24*(9), 2523-2531.

Brenner, J. S. (2007). Overuse injuries, overtraining, and burnout in child and adolescent athletes. *Pediatrics, 119*(6), 1242-1245.

Brown, L. E., & Greenwood, M. (2005). Periodization Essentials and Innovations in Resistance Training Protocols. *Strength & Conditioning Journal, 27*(4), 80-85.

Chatzopoulos, D., Galazoulas, C., Patikas, D., & Kotzamanidis, C. (2014). Acute effects of static and dynamic stretching on balance, agility, reaction time and movement time. *Journal of sports science & medicine, 13*(2), 403.

Claessens, A. L., & Lefevre, J. (1998). Morphological and performance characteristics as drop-out indicators in female gymnasts. *Journal of Sports Medicine and Physical Fitness, 38*(4), 305-309.

Costa, P., Ryan, E., Herda, T., Walter, A., Defreitas, J., Stout, J., & Cramer, J. (2013). Acute effects of static stretching on peak torque and the hamstrings-to-quadriceps conventional and functional ratios. *Scandinavian journal of medicine & science in sports, 23*(1), 38-45.

Costa, P. B., Herda, T. J., Herda, A. A., & Cramer, J. T. (2014). Effects of dynamic stretching on strength, muscle imbalance, and muscle activation. *Medicine & Science in Sports & Exercise, 46*(3), 586-593.

Coxon, J. P., Stinear, J. W., & Byblow, W. D. (2005). Amplitude of muscle stretch modulates corticomotor gain during passive movement. *Brain research, 1031*(1), 109-117.

Cramer, J. T., Housh, T. J., Johnson, G. O., Weir, J. P., Beck, T. W., & Coburn, J. W. (2007). An acute bout of static stretching does not affect maximal eccentric isokinetic peak torque, the joint angle at peak torque, mean power,

electromyography, or mechanomyography. *J Orthop Sports Phys Ther, 37*(3), 130-139. doi:10.2519/jospt.2007.2389
Critchfield, B. (2012). Stretching for dancers. *International Association for Dance Medicine and Science www. Dancescience. org. Accessed Nov*.
Curry, B. S., Chengkalath, D., Crouch, G. J., Romance, M., & Manns, P. J. (2009). Acute effects of dynamic stretching, static stretching, and light aerobic activity on muscular performance in women. *The Journal of Strength & Conditioning Research, 23*(6), 1811-1819.
Di Cagno, A., Baldari, C., Battaglia, C., Monteiro, M. D., Pappalardo, A., Piazza, M., & Guidetti, L. (2009). Factors influencing performance of competitive and amateur rhythmic gymnastics—Gender differences. *Journal of science and medicine in sport, 12*(3), 411-416.
Donti, O., Papia, K., Toubekis, A., Donti, A., Sands, W. A., & Bogdanis, G. C. (2017). Flexibility training in preadolescent female athletes: Acute and long-term effects of intermittent and continuous static stretching. *Journal of Sports Sciences*, 1-8.
Fletcher, I. M. (2010). The effect of different dynamic stretch velocities on jump performance. *European journal of applied physiology, 109*(3), 491-498.
Freitas, S., Vaz, J., Bruno, P., Andrade, R., & Mil-Homens, P. (2016). Stretching effects: high-intensity & moderate-duration vs. Low-intensity & long-duration. *International journal of sports medicine, 37*(03), 239-244.
Freitas, S. R., Mendes, B., Le Sant, G., Andrade, R. J., Nordez, A., & Milanovic, Z. (2017). Can chronic stretching change the muscle-tendon mechanical properties? A review. *Scandinavian Journal of Medicine & Science in Sports*.
Freitas, S. R., & Mil-Homens, P. (2015). Effect of 8-week high-intensity stretching training on biceps femoris architecture. *The Journal of Strength & Conditioning Research, 29*(6), 1737-1740.
Freitas, S. R., Vilarinho, D., Vaz, J. R., Bruno, P. M., Costa, P. B., & Mil-homens, P. (2015). Responses to static stretching are dependent on stretch intensity and duration. *Clinical physiology and functional imaging, 35*(6), 478-484.
Gajdosik, R. L. (2001). Passive extensibility of skeletal muscle: review of the literature with clinical implications. *Clinical biomechanics, 16*(2), 87-101.
Gruber, M., Linnamo, V., Strojnik, V., Rantalainen, T., & Avela, J. (2009). Excitability at the motoneuron pool and motor cortex is specifically modulated in lengthening compared to isometric contractions. *Journal of neurophysiology, 101*(4), 2030-2040.
Guissard, N., & Duchateau, J. (2004). Effect of static stretch training on neural and mechanical properties of the human plantar-flexor muscles. *Muscle & nerve, 29*(2), 248-255.
Guissard, N., & Duchateau, J. (2006). Neural aspects of muscle stretching. *Exercise and sport sciences reviews, 34*(4), 154-158.
Guissard, N., Duchateau, J., & Hainaut, K. (1988). Muscle stretching and motoneuron excitability. *European Journal of Applied Physiology and Occupational Physiology, 58*(1-2), 47-52.
Guissard, N., Duchateau, J., & Hainaut, K. (2001). Mechanisms of decreased motoneurone excitation during passive muscle stretching. *Experimental Brain Research, 137*(2), 163-169.
Harvey, L. A., Byak, A. J., Ostrovskaya, M., Glinsky, J., Katte, L., & Herbert, R. (2003). Randomised trial of the effects of four weeks of daily stretch on extensibility of hamstring muscles in people with spinal cord injuries. *Australian Journal of Physiotherapy, 49*(3), 176-181.

Herda, T. J., Costa, P. B., Walter, A. A., Ryan, E. D., Hoge, K. M., Kerksick, C. M., . . . Cramer, J. T. (2011). Effects of two modes of static stretching on muscle strength and stiffness. *Medicine & Science in Sports & Exercise, 43*(9), 1777-1784.
Kay, A. D., & Blazevich, A. J. (2012). Effect of acute static stretch on maximal muscle performance: a systematic review. *Med Sci Sports Exerc, 44*(1), 154-164. doi:10.1249/MSS.0b013e318225cb27
Kokkonen, J., Nelson, A. G., Eldredge, C., & Winchester, J. B. (2007). Chronic static stretching improves exercise performance. *Med Sci Sports Exerc, 39*(10), 1825-1831. doi:10.1249/mss.0b013e3181238a2b
Kraemer, W. J., & Ratamess, N. A. (2004). Fundamentals of resistance training: progression and exercise prescription. *Medicine and science in sports and exercise, 36*(4), 674-688.
Lamas, L., Ugrinowitsch, C., Rodacki, A., Pereira, G., Mattos, E. C., Kohn, A. F., & Tricoli, V. (2012). Effects of strength and power training on neuromuscular adaptations and jumping movement pattern and performance. *The Journal of Strength & Conditioning Research, 26*(12), 3335-3344.
LaRoche, D. P., Lussier, M. V., & Roy, S. J. (2008). Chronic stretching and voluntary muscle force. *The Journal of Strength & Conditioning Research, 22*(2), 589-596.
Letawsky, N. R., Schneider, R. G., Pedersen, P. M., & Palmer, C. J. (2003). Factors influencing the college selection process of student-athletes: Are their factors similar to non-athletes. *College Student Journal, 37*(4), 604-611.
Lima, C. D., Brown, L. E., Wong, M. A., Leyva, W. D., Pinto, R. S., Cadore, E. L., & Ruas, C. V. (2016). Acute Effects of Static vs. Ballistic Stretching on Strength and Muscular Fatigue Between Ballet Dancers and Resistance-Trained Women. *The Journal of Strength & Conditioning Research, 30*(11), 3220-3227.
Lorenz, D., & Morrison, S. (2015). Current concepts in periodization of strength and conditioning for the sports physical therapist. *International journal of sports physical therapy, 10*(6), 734.
Magnusson, S., Aagard, P., Simonsen, E., & Bojsen-Møller, F. (1998). A biomechanical evaluation of cyclic and static stretch in human skeletal muscle. *International journal of sports medicine, 19*(05), 310-316.
Magnusson, S., Simonsen, E. B., Aagaard, P., Boesen, J., Johannsen, F., & Kjaer, M. (1997). Determinants of musculoskeletal flexibility: viscoelastic properties, cross-sectional area, EMG and stretch tolerance. *Scandinavian Journal of Medicine & Science in Sports, 7*(4), 195-202.
Magnusson, S. P., Simonsen, E., Aagaard, P., Sørensen, H., & Kjaer, M. (1996). A mechanism for altered flexibility in human skeletal muscle. *The Journal of Physiology, 497*(Pt 1), 291.
Manoel, M. E., Harris-Love, M. O., Danoff, J. V., & Miller, T. A. (2008). Acute effects of static, dynamic, and proprioceptive neuromuscular facilitation stretching on muscle power in women. *The Journal of Strength & Conditioning Research, 22*(5), 1528-1534.
Miletić, Đ., Katić, R., & Maleš, B. (2004). Some anthropologic factors of performance in rhythmic gymnastics novices. *Collegium antropologicum, 28*(2), 727-737.
Morrin, N., & Redding, E. (2013). Acute effects of warm-up stretch protocols on balance, vertical jump height, and range of motion in dancers. *Journal of Dance Medicine & Science, 17*(1), 34-40.

Ms, G., Autumn, S., Jones, J., Ritchey, E. N., Murphy, C., Grimes, H., & Coons, J. M. (2014). The Acute Effects of a Dynamic Stretching Protocol on Wingate Performance. *International Journal of Exercise Science, 7*(4), 2.

Ogura, Y., Miyahara, Y., Naito, H., Katamoto, S., & Aoki, J. (2007). Duration of static stretching influences muscle force production in hamstring muscles. *J Strength Cond Res, 21*(3), 788-792. doi:10.1519/r-18785.1

Okamura, N., Tsukune, M., Kobayashi, Y., & Fujie, M. G. (2014). *A study of viscoelasticity index for evaluating muscle hypotonicity during static stretching.* Paper presented at the Engineering in Medicine and Biology Society (EMBC), 2014 36th Annual International Conference of the IEEE.

Opplert, J., & Babault, N. (2017). Acute Effects of Dynamic Stretching on Muscle Flexibility and Performance: An Analysis of the Current Literature. *Sports Medicine*, 1-27.

Page, P. (2012). Current concepts in muscle stretching for exercise and rehabilitation. *International journal of sports physical therapy, 7*(1), 109.

Ploutz-Snyder, L. L., & Giamis, E. (2001). Orientation and familiarization to 1RM strength testing in old and young women. *The Journal of Strength & Conditioning Research, 15*(4), 519-523.

Pope, R. P., Herbert, R. D., Kirwan, J. D., & Graham, B. J. (2000). A randomized trial of preexercise stretching for prevention of lower-limb injury. *Med Sci Sports Exerc, 32*(2), 271-277.

Prestes, J., Frollini, A. B., de Lima, C., Donatto, F. F., Foschini, D., de Cássia Marqueti, R., . . . Fleck, S. J. (2009). Comparison between linear and daily undulating periodized resistance training to increase strength. *The Journal of Strength & Conditioning Research, 23*(9), 2437-2442.

Rhea, M. R., & Alderman, B. L. (2004). A meta-analysis of periodized versus nonperiodized strength and power training programs. *Research Quarterly for Exercise and Sport, 75*(4), 413-422.

Rhea, M. R., Ball, S. D., Phillips, W. T., & Burkett, L. N. (2002). A comparison of linear and daily undulating periodized programs with equated volume and intensity for strength. *The Journal of Strength & Conditioning Research, 16*(2), 250-255.

Ryan, E. D., Beck, T. W., Herda, T. J., Hull, H. R., Hartman, M. J., Costa, P. B., . . . Cramer, J. T. (2008). The time course of musculotendinous stiffness responses following different durations of passive stretching. *J Orthop Sports Phys Ther, 38*(10), 632-639. doi:10.2519/jospt.2008.2843

Samson, M., Button, D. C., Chaouachi, A., & Behm, D. G. (2012). Effects of dynamic and static stretching within general and activity specific warm-up protocols. *Journal of sports science & medicine, 11*(2), 279.

Shrier, I. (2004). Does stretching improve performance?: a systematic and critical review of the literature. *Clinical Journal of sport medicine, 14*(5), 267-273.

Trajano, G. S., Nosaka, K., & Blazevich, A. J. (2017). Neurophysiological mechanisms underpinning stretch-induced force loss. *Sports Medicine*, 1-11.

Trajano, G. S., Seitz, L. B., Nosaka, K., & Blazevich, A. J. (2014). Can passive stretch inhibit motoneuron facilitation in the human plantar flexors? *Journal of Applied Physiology, 117*(12), 1486-1492.

Unick, J., Kieffer, H. S., Cheesman, W., & Feeney, A. (2005). The acute effects of static and ballistic stretching on vertical jump performance in trained women. *The Journal of Strength & Conditioning Research, 19*(1), 206-212.

Vain, A., & Kums, T. (2002). Criteria for preventing overtraining of the musculoskeletal system of gymnasts. *Biology of sport, 19*(4), 329-346.

Wallmann, H. W., Christensen, S. D., Perry, C., & Hoover, D. L. (2012). THE ACUTE EFFECTS OF VARIOUS TYPES OF STRETCHING STATIC, DYNAMIC, BALLISTIC, AND NO STRETCH OF THE ILIOPSOAS ON 40-YARD SPRINT TIMES IN RECREATIONAL RUNNERS. *International journal of sports physical therapy, 7*(5), 540.

Weppler, C. H., & Magnusson, S. P. (2010). Increasing muscle extensibility: a matter of increasing length or modifying sensation? *Physical therapy, 90*(3), 438-449.

Williams, T. D., Tolusso, D. V., Fedewa, M. V., & Esco, M. R. (2017). Comparison of Periodized and Non-Periodized Resistance Training on Maximal Strength: A Meta-Analysis. *Sports Medicine*, 1-18.

Wyon, M. (2010). Stretching for Dance.

Young, W., Elias, G., & Power, J. (2006). Effects of static stretching volume and intensity on plantar flexor explosive force production and range of motion. *Journal of Sports Medicine and Physical Fitness, 46*(3), 403.

Chapter 2: Co-Authorship Statement

The following details of my role in the preparation of the manuscript are presented below.

Research Design

Methodology was developed based on previous research by me and Dr. David Behm. Many meetings between me and Dr. David Behm were held to discuss the literature and ensure that the research question would be appropriate to what has been done in the literature and practical field. With assistance from Dr. David Behm I was able to obtain approval from the Health Research Ethics Authority (HREA) to conduct this research.

Data Collection

All data was collected by me with assistance of Yimeng Li and Nehara Herat.

Data Analysis

I performed all data analysis procedures.

Manuscript Preparation

I wrote the manuscript with assistance of Dr. David Behm.

Chapter 3: Manuscript

The Effects of Periodized versus Non-Periodized Stretch Training Programs on Morphological Flexibility Adaptations and Muscle Performance in Artistic Gymnasts

Authors: Camila D. Lima[1], Yimeng Li[1], Nehara Herat[1] and David G. Behm[1]

Institution: [1]School of Human Kinetics and Recreation Memorial University of Newfoundland St. John's, Newfoundland, Canada, A1M 3L8

2.0 Introduction

Static stretching (SS) is a popular technique performed to increase joint flexibility by lengthening elastic structures to a specific point and holding the position for a period of time [1-5]. Acute prolonged SS has consistently been reported to induce maximal force and power output impairments [2,4,5]. There are many studies showing the positive effects of long-term SS on flexibility albeit with controversial results regarding muscle performance output [8, 81]. Long-term stretching programs (>8 weeks) may improve muscle performance, with measures such as jump height and maximal dynamic contractions [81, 85]. Medeiros et al. in a meta-analysis found that flexibility training improved functional tests, isotonic and isometric contractions. Kokkonen et al. attributed the gain in power to increases in muscle length.

A modification of sensation (stretch tolerance) has been implicated as a major factor influencing SS-induced increases in flexibility[5, 83, 86]. However, whether stretch tolerance works in isolation has been questioned by numerous studies showing morphological and neurological adaptations after stretch training[29, 31, 32, 40, 87]. Neurological adaptations have been associated with decrements in spinal excitability[31], afferent reflex disfacilitation to the motoneurone pool[26, 27] or enhancement of pre-synaptic inhibition as measured with the Hoffman reflex (H-reflex) amplitude[31]. Guissard et al.[32] found that 30% increases in ankle dorsiflexion range of motion (ROM) following six weeks of SS training was accompanied by a reduction of passive stiffness and H-reflex decrements. Whereas, acute SS responses (i.e. improved ROM and performance impairments) in many studies have been attributed to neurological adaptations [2, 4, 10, 27], chronic SS interventions generally lead to morphological adaptations, such as decreases in muscle-tendon stiffness and increases in fascicle length. Nevertheless, Freitas et al. [88] suggested in a comprehensive review that a short period of SS training may not be sufficient to elicit changes in passive torque and decrements in stiffness. A general limitation of studies exploring SS long-term effects is the lack of manipulation of training variables such as frequency, intensity and sets over the training period.

SS is a common technique performed within sports like artistic, rhythmic and trampoline gymnastics, figure skating and dance that requires athletes to perform movements at a very high degree of ROM, while maintaining their maximal force and power output. However, SS may actually cause impairments on these performances. For instance, BS and SS can cause decreases on hamstrings peak torque for resistance trained and ballerinas, although BS may increase muscle endurance for ballerinas[1]. One of the main objectives of the highly flexible population training is to achieve maximal performance at maximal flexibility. Therefore, competitive gymnasts typically spend over 25 hours per week practicing skills that involves a combination of flexibility, power, balance and force[89]. They are evaluated at the competition by judges that follow a strict code of points developed by the International Gymnastics Federation, which requires gymnasts to perform a skill at a specific ROM. This leads to specific execution deductions in their overall score when these requirements are not followed. In many cases at a high level international competition, there may be extremely small differences (i.e. fractions) in the final score of the first and second place gymnast, which could be related to execution errors such as the gymnast failing to perform a specific powerful skill at a specific degree of ROM. Many clubs perform auditions to evaluate new gymnasts to be part of the competitive team based on their initial flexibility levels.

Most competitive gymnasts have been performing similar exhaustive high volume stretch training for years without knowing whether there would be more efficient training regimens. Perhaps, longer recovery times between stretching bouts could induce greater neuromuscular system adaptations. For example, periodized (PD) strength training has been commonly used by athletes and the general population to provide greater strength and power gains by regulating physiological responses over longer periods of recovery, thus decreasing the likelihood of overtraining effects. There are a variety of periodization modes used within the literature, however the most popular training programs are linear and undulating periodization[33, 63, 90]. Linear periodization includes modulation of training variables over longer microcycles, whereas undulating periodization aims to modulate these variable during smaller microcycles[33]. There is a strong body of research showing greater muscle performance increases after periodization training while avoiding mental and musculoskeletal exhaustion[34, 36, 60]. Although some studies have suggested no changes in force outcome after a linear versus non periodization (NP)[37, 91], they suggested that periodized programs may be a safer training method to keep the athletes fully motivated and to avoid adverse effects. The neuromuscular system needs to receive sufficient regulated stress to induce greater adaptations. This is the case with highly strength or power trained individuals that have reached an adaptation window or plateau that does not provide further stimulus to the neuromuscular system. However, to the best of our knowledge, no previous study has employed periodized stretch training interventions to investigate long-term stretching adaptations. Such a program could provide greater information regarding physiological aspects of flexibility gains. Hence, the objective of this study was to investigate linear versus non-periodized stretch training programs with artistic gymnasts over an 8-week flexibility program. It was hypothesized that periodized stretch training would provide greater increases in flexibility, thus inducing greater changes in stiffness without causing impairments in muscle performance.

2.1 Methods

2.1.1 Participants

An a priori power analysis (software package, G * Power 3.1.9.2) was used to calculate the sample size of this study using a statistical power of 0.8, correlation between groups of 0.5, and alpha level of $p < 0.05$. Based on previous studies [1, 31, 92-94], a sample size of 6.6 participants per group was calculated to achieve the desired statistical power. However, eight participants per group were adopted to ensure that in cases of attrition, the sample size would still be sufficient.

Sixteen artistic gymnasts' girls were allocated to two different groups: no periodization (NP, n = 8, age 11.50 ± 0.95 yrs., height 140.40 ± 4.98 cm, mass 31.62 ± 3.60 kg) and linear periodization (PD, n = 8, age 12.12 ± 2.03 yrs., height 150.62 ± 9.32, mass 40.15 ± 10.82 kg). All participants regularly practiced artistic gymnastics two to three times per week for at least 2 years. Participants were free from any recent knee and ankle musculoskeletal injuries that may inhibit maximal performance. All participants' parent or guardian read and signed an informed consent form approved by Interdisciplinary Committee on Ethics in Human Research (20171999-HK).

2.1.2 Experimental Design

In the PD group, participants had training variables progressively modified by increasing the number of stretch exercises and sets every two weeks (Table 1). In the NP group, participants performed one set of the same stretch exercises over an 8-week training period (Table 2). Both groups performed the stretching exercises at maximal intensity (maximal point of discomfort). The 8-week training program was performed three times per week in the gymnastics club supervised by the researcher. All participants' were measured pre- and post-training for hamstrings and dorsiflexors stiffness and passive torque, quadriceps fatigue, quadriceps and hamstrings peak torque, countermovement jump and hip extensors, and hip flexors and ankle dorsiflexors ROM (Figure 1). All pre- and post-tests were performed on two days separated by 48 hours, one week before and after the training intervention.

PLACE TABLES 1 AND 2 AND FIGURE 1 APPROXIMATELY HERE

2.1.3 Pre- and Post- Training Tests

On day one, participants were measured for height and mass, followed by a dynamic warm up (2 x10 m of knee hugs, walking lunges, and walking alternating toe touch), three ROM tests for hip flexors, hip extensors and ankle dorsiflexors, and hamstrings and gastrocnemius stiffness measures. All the testing measures were performed in a counterbalanced order. On day two, participants performed the same warm-up as the first session, followed by a countermovement jump performance test, hamstrings and quadriceps peak torque (PT) measures, and fatigue test (FT). Subjects were fitted with electromyography (EMG) electrodes in order to measure muscle activation during passive torque, PT, and FT.

2.1.4 Hamstrings Passive Torque

Participants laid in a supine position on the isokinetic dynamometer chair. Their pelvis and their right leg were strapped to avoid extranneous movement. A knee extensor and ankle brace was attached to their right leg to ensure that they were tested with knee fully extended and ankle at a neutral position. A pad was also attached to their lumbar spine to avoid pelvis rotation and maintain natural lumbar lordosis. Their right leg was passively moved by the researcher towards their chest and held for two seconds until the point that participants indicated their maximal ROM. The ROM used for the passive torque (stiffness) test was calculated using 80% of their maximal ROM to ensure that participants were fully comfortable with the procedures. For this, a familiarization session was conducted, where the dynamometer passively moved their right leg from the neutral position (dynamometer angle = 0°) to 80% of their maximal ROM at a constant velocity of $5°.s^{-1}$ for four repetitions. Finally, participants were tested for the final test where five more repetitions were conducted using the same procedures. Bipolar electrodes were attached on their biceps femoris (BF) and rectus femoris (RF) to ensure that no active contraction was performed. Data were discarded if participants had BF and RF EMG activation higher than 1% of their PT. The limb was weighed for gravity corrections. The procedures of hamstrings passive torque were based on previous study using similar procedures, which has found high reliability for these test.[4] (Figure 2)

2.1.5 Data reduction

Passive stiffness was calculated by the ratio of change in passive torque to the change in displacement of the angle ($\Delta T/ \Delta A$) [77]. The third repetition of passive torque and angle data were fitted using a fourth-order polynomial equation ($T(\theta) = m\theta^4 + n\theta^3 + o\theta^2 + p\theta + q$) to ensure that less error would be added to the data. The derivative of the polynomial equation was used to calculate the slope between angle and torque, which identified stiffness values: ($MTS= 4m\theta^3 + 3n\theta^2 + 2o\theta + p$). All the calculations were performed using a custom software Matlab (The Mathworks, Natick, USA).

2.1.6 Range of Motion (ROM) Tests

With all ROM measures, subjects were passively moved to the point of moderate discomfort (5 of 10 on a discomfort/pain scale) where the participant said "stop" and the goniometer position was recorded. Three trials were performed with 15-second rest between trials. The average of the three trials was taken for further analysis.

2.1.7 Hip flexors ROM

Participants laid in a supine position on a massage table with their hips over the edge. A digital goniometer (model HG1, HALO Medical Devices, Australia) was strapped on their right thigh. They were instructed to pull their left knee toward their chest, while an assistant pressed that knee and their shoulders against the table. The researcher held their right leg parallel to the floor and in a 90˚ position from the heel to the knee, which was considered the start position (goniometer = 0). From this position, the right knee was pressed down towards to the ground.[95]

2.1.8 Hamstrings ROM

Participants laid in a supine position on a massage table, and the researcher passively moved their right leg with the knee extended towards their chest. The opposite leg was kept extended by an assistant. A digital goniometer was placed on the back of their right leg. The researcher held their right hip parallel to the floor at 90˚ position, which was considered the start position (goniometer = 0). From this position, their hip was passively moved towards their chest.[96]

2.1.9 Gastrocnemius ROM

Participants laid in a supine position on a massage table with their knees extended. The researcher placed their right ankle at a neutral position (start position) where the goniometer indicated 0°. From this position, their ankle was passively moved to a point of moderate discomfort.[97]

2.1.10 Vertical Jump Tests

CMJ was performed using a Vertec® (Gill Athletics Inc, Champaign, IL, USA) device to measure jump height. Prior their jump performance, participants were asked to stand next to the Vertec device using their dominant arm to reach and touch the lowest visual vane, where their reach height was taken to correctly adjust the device height. Participants started in a standing position with their shoulders flexed at 90 degrees. After the researcher's command, participants performed a rapid squat movement to a self-selected squatting position, and then jumped vertically as high and fast as possible with arm swing and no pause at the bottom. Three attempts were provided to participants. The average of three repetitions of each vertical jump test was considered for further analyses[98, 99].

2.1.11 Peak Torque

Peak torque measures for hamstrings and quadriceps were performed on a Humac Norm isokinetic dynamometer (Cybex NORM®, Humac, CA, USA). Participants were seated on the dynamometer chair with straps across their chest, hips and thighs. The dynamometer lever arm was attached above their right medial malleolus. They were asked to hold their arms across their chest for the entire test. A familiarization was conducted consisting of three maximal knee-extension isokinetic concentric contractions at $60°.s^{-1}$. After the familiarization, participants were asked to perform five maximal knee extension-flexion isokinetic concentric repetitions at $60°.s^{-1}$, from 90° (knee flexion) to 0° (knee extension) of ROM. The highest quadriceps and hamstrings PT values across all repetitions were used for further analysis [100]. Verbal encouragement was provided during the test. Participants had EMG electrodes placed on their RF and BF. [101]

2.1.12 Fatigue Test

Participants were seated on the isokinetic dynamometer chair using the same procedures as the isokinetic PT test. They were then asked to perform 30 maximal concentric knee extension repetitions at $180°.s^{-1}$. To assess leg fatigue, the mean of the first 3 repetitions was used to compare with the mean of the last three repetitions. [102, 103]

2.1.13 Electromyography

The skin electrode placement was performed after shaving the hair of the skin and using isopropyl alcohol swabs to reduce the resistance. To measure the quadriceps and hamstrings muscle activity, separate bipolar (2cm center to center) surface electrodes Ag/AgCl were placed on the skin at the RF, TA, GM and BF muscle belly. A reference electrode was placed on the lateral malleolus. EMG was recorded with a customized software Signal 5 (Cambridge Electronic Design Ltd., Cambridge, UK) at a sample rate of 2000 Hz (impedance = 2 MΩ, common mode rejection ratio > 110 dB min (50/60 Hz), noise> 5 μV). A bandpass filter of 10Hz -500Hz and the gain at 1000 were also set. Root mean square (RMS) was calculated over a 1s plateau of the curve during each knee extension and flexion for PT and FT tests.

Stretch Training Procedures

Both PD and NP groups trained three times per week for 8 weeks. They performed only static stretching at an intensity level of ten from a scale of discomfort from 1 to 10 [1, 104]. All participants performed nine stretching exercises (three stretches for each muscle group). The PD group progressively increased the number of stretch exercises and repetitions (starting from three to nine) for each microcycle (2 weeks) (Table 1). The no periodization group performed one set of all the nine stretching exercises from the beginning of the stretching program to the 8 weeks (Table 2). The stretching exercises included the following stretches:

2.1.14 Hamstrings

Sitting Toe Touch on the bench. Participants sat on the floor with their legs extended on the bench. One hand was placed on top of the other, and they were asked to reach forward toward their feet as far as possible while keeping their knees flat on a bench (Figure 3).

Sitting Toe Touch. Participants sat on the floor with their legs extended. One hand was placed on top of the other, and they reached forward toward their feet as far as possible while keeping their knees flat on the ground. (Figure 4).

Lying Hamstrings. Participants laid in supine position on the floor and pulled one leg with knee extended to their chest. They were asked to keep their opposite leg extended and on the floor. (Figure 5).

2.1.15 Quadriceps

Hip Flexors. Participants squatted on the floor with one knee flexed in front and the opposite leg extended behind them. They were asked to keep their trunk straight and stable. (Figure 6).

Hip Flexors Kneeling. Participants squatted on the floor with one knee flexed in front and the opposite leg extended behind them. They were asked to pull their flexed knee with the opposite arm taking their heels towards their hips, while keeping their trunk straight and stable. (Figure 7).

Prone Quadriceps. Participants laid in a pronated position on the floor and flexed one knee while pulling it toward their back. (Figure 8).

2.1.16 Gastrocnemius

Pushing the wall. In a standing position participants kept one leg flexed in front and the opposite leg extended posteriorly. They were asked to push the wall with their hands to increase extension of the back leg (Figure 9)

Standing on a bench. With a standing position, participants kept the ball (distal segment of tarsals) of their feet on a step of a bench and pressed their heels down (dorsiflexion) (Figure 10).

Sitting and Pulling. Participants sat on the ground with their trunk straight and both legs extended. They were asked to pull their ankle to a dorsiflexion position using an elastic band (Figure 11).

2.2 Statistical Analyses

All data are expressed as mean and standard deviation (SD), and analyses were performed with SPSS 23.0 software (Chicago, IL, USA). An alpha level of 0.05 was used to determine statistical significance. The normality of all values was verified using the Shapiro Wilk test. Levene's test was used to check the homogeneity of variance for all tests. Three-way repeated measures (ANOVA) [2 groups (periodization and no periodization) X 2 times (pre-training and post-training) X 11 angles (from 0° to 11°)] were used to identify differences in hamstrings stiffness and passive torque. Two-way repeated measures, [2 times (pre-training and post-training) x 2 groups (periodization and no periodization)] were used to analyze changes in hamstrings and quadriceps peak torque, countermovement jump height (CMJ), rectus femoris (RF) and biceps femoris (BF) electromyography (EMG) activity, hip flexors, hip extensors and dorsiflexors ROM, and fatigue index. One way repeated measures and post-hoc (LSD) were used to examine specific interactions and main effects. Effect sizes for each significant difference were calculated using Cohens *d equation (ES = Post test mean – Pre test mean/ Pre test SD)*, in which values < 0.25 were considered trivial, 0.25-0.5 small, 0.50-1.0 moderate, and > 1.0 large based on highly trained subjects.[105]

2.3 Results

For CMJ there was no interaction for group and time (p =0.15). Effect sizes indicated that the periodization group had moderate (ES = 0.5) magnitude of change for increases in CMJ height compared to the NP group, who had trivial (ES = 0.2) magnitude of change. However, there was a main effect for time (p < 0.001), where both groups had greater CMJ height at post-training (38.36 ± 7.92 cm) compared to pre-training (35.48 ± 1.98 cm). (Figure 12)

For quadriceps PT, there was no interaction for group and time (p =0.49) or main effect for time (p=0.09), with trivial magnitude of change for both groups (ES = 0.1). (Figure 13)

For hamstrings PT, there was no interaction effect for group and time (p = 0.25). However, there was a main effect for time (p= 0.01), where hamstrings PT demonstrated greater values at the post-training test (52 ± 17.52 $N.m^{-1}$) compared to pre-training test (48.17 ± 18.57 $N.m^{-1}$). Effects sizes indicated a moderate magnitude (ES = 0.5) of change for the no periodized group compared to a trivial magnitude (ES = 0.1) of change for periodized group. (Figure 14)

For the fatigue index, there was no interaction between group and time (p = 0.1) or main effect for time (p= 0.85). Effects sizes indicated a moderate (ES = 0.6) magnitude of change for the no periodization group compared to a trivial (ES = 0.2) magnitude of change for periodized group. (Figure 15)

There was no interaction for RF ($p = 0.95$) or BF ($p= 0.23$) EMG with near significant main effects for time for RF ($p = 0.06$) and BF ($p = 0.11$) EMG activity, respectively. For RF effects size analysis indicated a moderate (ES = 0.8) magnitude of change for periodized group compared to a large (ES > 1.0) magnitude of change for no periodized group. For BF a large (ES > 1.0) magnitude of change was indicated for the periodized group compared to a small (ES = 0.3) magnitude of change for no periodized group. (Table 3)

For hip extensors ($p = 0.18$), hip flexors ($p = 0.36$) and dorsiflexors ($p = 0.90$) ROM there was no interaction effects between time and group. However, there was a main effect for time ($p < 0.01$) which showed pre- to post-training increases in hip flexors (21.20 ± 6.02), (28.25 ± 6.55), hip extensors (33.89 ± 9.04), (42.45 ± 13.80) and dorsiflexors (53.00 ± 11.88) (65.62 ± 12.47) ROM, respectively. (Table 4)

A two-way interaction was found between time and angle for hamstrings stiffness ($p = 0.01$). A one way repeated measures for angle found no difference between angles for the pre-training results. However, there decreases for all the angles compared to the first angle for post-training ($p = 0.03$). (Figure 16) (Table 5)

A two-way repeated measures interaction was found between time and angle ($p = 0.01$) for hamstrings passive torque. A one-way repeated measures analysis for ankle found no difference between angles for the pre-training results. However, there were decreases for all the angles compared to the first four angles for post-training ($p = 0.01$) measures. (Figure 17) (Table 6).

2.4 Discussion

The purpose of this study was to investigate and compare the effects of a periodized versus non-periodized stretch training program on hip flexors, extensors and dorsiflexors ROM, hamstrings stiffness and muscle performance. The results of this study demonstrated that overall, an 8-week periodized stretch training program was not sufficient to elicit different muscle adaptations compared to a no periodization program. However, both stretch training programs led to increases in hamstrings, quadriceps and dorsiflexors ROM, which may be explained by the decreases in hamstrings stiffness. There were also positive responses for some muscle performance variables, such as increases in CMJ height and hamstrings PT. However, although both training programs led to long-term positive effects on muscle performance and flexibility, BF and RF EMG, quadriceps PT and fatigue index remained similar from pre- to post-training.

Previous studies have found substantial flexibility increases after SS programs over short and longer periods of training (4 to 12 weeks). This is in agreement with our results since we found relevant increases after 8-week of SS program for different muscle groups. Additionally, we did not find significant changes in ROM between training groups, however the effects sizes for hamstrings and quadriceps ROM demonstrated that the periodized training group had greater magnitude increases in ROM. Although the most advantageous periodization strategies for strength training programs have been in constant debate, to the best of our knowledge our study is the first to investigate the effect of periodization with stretch training.

Periodized strength training has been universally adopted by coaches to increase strength gains. However, the literature seems to be still uncertain whether this training strategy is actually effective in eliciting greater improvements in performance. Baker et al.[106] compared three different strength training models: undulating, linear and no periodization on strength and vertical jump. They found increases in VJ and squat performance after all training groups, with no differences between groups. They associated these findings to their study design, which included highly trained participants and a short term program. Although the focus of our periodization training program was on flexibility gains, the findings of Baker et al. study are in accordance with our results, since our participants were highly flexible gymnasts that performed a training program lasting only eight weeks. This time period may not have been sufficient to induce any significantly different adaptations between both groups. Hoffman et al.[107] also investigated linear versus non-linear periodized strength training programs with American Football players over 15 weeks and did not find any differences in strength gains between both groups. However, in an extensive meta analyses performed by Rhea et al.[105] comparing linear periodized and non-periodized strength and power training programs they concluded that linear periodized training had superior effects on strength and power gains compared to non-periodized training regardless of participants' training background, age and sex. However, they found that training programs shorter than eight weeks were less effective than training programs lasting from nine to twenty weeks. Although our results demonstrated that both periodized and non periodized stretch training are effective in increasing hamstrings, quadriceps and ankle flexibility for both groups, there was a larger magnitude of change for the linear periodized stretch training programs. Therefore, a higher number of participants and a longer stretch training program could have elicited greater adaptations in flexibility for the periodized group. This demonstrates that long-term linear periodized stretch training may be a more effective method for creating greater flexibility adaptations. However, it is important to be acknowledged that the linear periodized stretch training may have slightly greater volume than non periodized stretch training.

Although, changes in stretch tolerance have been highlighted as the main explanation for flexibility improvements [5, 9, 10], research evidence has suggested that long-term stretching programs may also cause alterations in the morphology of the elastic tissues, which may lead to plastic changes in these structures. Marshall et al.[108] found that four weeks of stretch training for hamstrings performed five times per week induced a reduction of 31% in passive stiffness. Their findings are in accordance with our results since we found decrements in hamstrings passive stiffness after an 8-week intervention. This suggests that morphological adaptations may also occur after longer stretching interventions. Marshal et al. also did not encounter changes in stretch tolerance, which brings to attention that morphological adaptations may also explain flexibility increases. However, we did not measure stretch tolerance to support their results. Similarly, Magnusson et al.[86] investigated hamstrings stiffness and stretch tolerance after three weeks of hamstrings stretching exercises. They did not find any differences in hamstrings stiffness after the short-term stretch training, therefore they related the flexibility increases as a consequence of an increase in stretch tolerance. Although the present study found a decrease in hamstrings stiffness, it does not preclude the possible contribution of increased stretch tolerance as well. However, the lack of change in hamstrings stiffness found in their study may be related to the duration of the stretching program (three weeks). Additionally, Freitas et al.[88] in a recent review that involved over 26 articles suggested that shorter periods of stretch training may only cause alterations in stretch tolerance rather than any morphological adaptations. Our results demonstrate that an 8-week of stretch training program may be sufficient to elicit changes in hamstrings stiffness.

Although acute effects of stretching seem to cause decrements in muscle performance such as decreases in the muscle capacity to exert maximal force and power, long-term stretch training programs may cause a positive outcome in muscle performance. Medeiros et al.[85] in a review found that chronic stretching programs induce greater response on functional test and dynamic contractions. Similarly, we found that both periodized and non-periodized stretch training programs led to an increase in CMJ and hamstrings PT. However, we did not find any changes in quadriceps concentric PT and fatigue index for any group. This different stretching response between hamstrings and quadriceps may be related to the hamstrings muscle groups having smaller number of muscles, muscle architecture, force producing capabilities and cross sectional area. ROM capacity and muscle architecture between hamstrings and quadriceps muscle groups Our effect size results also showed that there was a trend for greater BF activity for the periodized group, and an overall higher RF activity after both training programs. Although we found a decrease in hamstrings stiffness, this appears to not have affected the hamstrings muscle force. This, may have occurred due to an increase in muscle length after both stretch training programs. Therefore, periodized and non-periodized stretch training led to increases in muscle flexibility, which may have led to greater recruitment of sarcomeres in series.

Kokkonen et al.[81] found that after a 6-week stretching program there were increases in vertical jump, knee-extension and endurance. They suggested that flexibility training leads to force gains, but is not a substitute for strength training. Our results are in agreement with their findings since we also found a higher CMJ height for both stretch training groups. This increase in CMJ height may be related to the increase in quadriceps flexibility leading to greater capacity of displacement of the elastic tissues and increases in concentric quadriceps force. CMJ involves stretch shortening cycle where there is rapid quadriceps eccentric action and elongation of gastrocnemius muscles followed by a concentric action of the quadriceps. The greater elongation of these muscles after stretch training may have improved the elastic storage energy capacity of the quadriceps and gastrocnemius augmenting subsequent force concentric output.

2.5 Conclusion

The findings of this study demonstrate that eight weeks of SS increases ROM, hamstrings PT, CMJ and decreases hamstrings stiffness, regardless if the training is periodized or not. This indicates that the flexibility gains after SS may be related to morphological changes. Furthermore, although there were no differences between both groups in any variable, the ES results indicated that the periodized stretch training group presented greater magnitude increases in flexibility compared to the non-periodized stretch training group.

2.6 References

1. Lima CD, Brown LE, Wong MA, et al. Acute Effects of Static vs. Ballistic Stretching on Strength and Muscular Fatigue Between Ballet Dancers and Resistance-Trained Women. *J Strength Cond Res.* 2016; 30(11):3220-3227.
2. Behm DG, Chaouachi A. A review of the acute effects of static and dynamic stretching on performance. *Eur J Appl Physiol.* 2011; 111(11):2633-2651.
3. Samson M, Button DC, Chaouachi A, Behm DG. Effects of dynamic and static stretching within general and activity specific warm-up protocols. *J Sports Sci Med.* 2012; 11(2):279 -285.
4. Kay AD, Blazevich AJ. Effect of acute static stretch on maximal muscle performance: a systematic review. *Med Sci Sports Exerc.* 2012; 44(1):154-164.
5. Behm DG, Blazevich AJ, Kay AD, McHugh M. Acute effects of muscle stretching on physical performance, range of motion, and injury incidence in healthy active individuals: a systematic review. *Appl Physiol Nutr Metab.* 2016; 41(1):1-11.
6. Curry BS, Chengkalath D, Crouch GJ, Romance M, Manns PJ. Acute effects of dynamic stretching, static stretching, and light aerobic activity on muscular performance in women. *The Journal of Strength & Conditioning Research.* 2009; 23(6):1811-1819.
7. Page P. Current concepts in muscle stretching for exercise and rehabilitation. *International journal of sports physical therapy.* 2012; 7(1):109.
8. Bandy WD, Irion JM, Briggler M. The effect of static stretch and dynamic range of motion training on the flexibility of the hamstring muscles. *Journal of Orthopaedic & Sports Physical Therapy.* 1998; 27(4):295-300.

9. Bacurau RF, Monteiro GA, Ugrinowitsch C, Tricoli V, Cabral LF, Aoki MS. Acute effect of a ballistic and a static stretching exercise bout on flexibility and maximal strength. *J Strength Cond Res.* 2009; 23(1):304-308.
10. Behm DG, Blazevich AJ, Kay AD, McHugh M. Acute effects of muscle stretching on physical performance, range of motion, and injury incidence in healthy active individuals: a systematic review. *App Physiol Nut Metab.* 2015; 41(1):1-11.
11. Fletcher IM. The effect of different dynamic stretch velocities on jump performance. *European journal of applied physiology.* 2010; 109(3):491-498.
12. Opplert J, Babault N. Acute Effects of Dynamic Stretching on Muscle Flexibility and Performance: An Analysis of the Current Literature. *Sports Medicine.* 2017:1-27.
13. Aguilar AJ, DiStefano LJ, Brown CN, Herman DC, Guskiewicz KM, Padua DA. A dynamic warm-up model increases quadriceps strength and hamstring flexibility. *The Journal of Strength & Conditioning Research.* 2012; 26(4):1130-1141.
14. Chatzopoulos D, Galazoulas C, Patikas D, Kotzamanidis C. Acute effects of static and dynamic stretching on balance, agility, reaction time and movement time. *Journal of sports science & medicine.* 2014; 13(2):403.
15. Costa PB, Herda TJ, Herda AA, Cramer JT. Effects of dynamic stretching on strength, muscle imbalance, and muscle activation. *Medicine & Science in Sports & Exercise.* 2014; 46(3):586-593.
16. Ms G, Autumn S, Jones J, et al. The Acute Effects of a Dynamic Stretching Protocol on Wingate Performance. *International Journal of Exercise Science.* 2014; 7(4):2.
17. Wyon M. Stretching for Dance. 2010.
18. Barroso R, Tricoli V, Santos Gil SD, Ugrinowitsch C, Roschel H. Maximal strength, number of repetitions, and total volume are differently affected by static-, ballistic-, and proprioceptive neuromuscular facilitation stretching. *J Strength Cond Res.* 2012; 26(9):2432-2437.
19. Donti O, Papia K, Toubekis A, Donti A, Sands WA, Bogdanis GC. Flexibility training in preadolescent female athletes: Acute and long-term effects of intermittent and continuous static stretching. *Journal of Sports Sciences.* 2017:1-8.
20. Ploutz-Snyder LL, Giamis E. Orientation and familiarization to 1RM strength testing in old and young women. *The Journal of Strength & Conditioning Research.* 2001; 15(4):519-523.
21. Ayala F, de Baranda PS, Croix MDS, Santonja F. Reproducibility and criterion-related validity of the sit and reach test and toe touch test for estimating hamstring flexibility in recreationally active young adults. *Physical Therapy in Sport.* 2012; 13(4):219-226.
22. Bozic PR, Pazin NR, Berjan BB, Planic NM, Cuk ID. Evaluation of the field tests of flexibility of the lower extremity: reliability and the concurrent and factorial validity. *The Journal of Strength & Conditioning Research.* 2010; 24(9):2523-2531.

23. Freitas SR, Mendes B, Le Sant G, Andrade RJ, Nordez A, Milanovic Z. Can chronic stretching change the muscle-tendon mechanical properties? A review. *Scandinavian Journal of Medicine & Science in Sports.* 2017.
24. Magnusson SP, Simonsen E, Aagaard P, Sørensen H, Kjaer M. A mechanism for altered flexibility in human skeletal muscle. *The Journal of Physiology.* 1996; 497(Pt 1):291.
25. Ryan ED, Beck TW, Herda TJ, et al. The time course of musculotendinous stiffness responses following different durations of passive stretching. *J Orthop Sports Phys Ther.* 2008; 38(10):632-639.
26. Trajano GS, Seitz LB, Nosaka K, Blazevich AJ. Can passive stretch inhibit motoneuron facilitation in the human plantar flexors? *Journal of applied physiology.* 2014; 117(12):1486-1492.
27. Trajano GS, Nosaka K, Blazevich AJ. Neurophysiological mechanisms underpinning stretch-induced force loss. *Sports Medicine.* 2017:1-11.
28. Weppler CH, Magnusson SP. Increasing muscle extensibility: a matter of increasing length or modifying sensation? *Physical therapy.* 2010; 90(3):438-449.
29. Guissard N, Duchateau J, Hainaut K. Mechanisms of decreased motoneurone excitation during passive muscle stretching. *Experimental Brain Research.* 2001; 137(2):163-169.
30. Guissard N, Duchateau J, Hainaut K. Muscle stretching and motoneuron excitability. *European Journal of Applied Physiology and Occupational Physiology.* 1988; 58(1-2):47-52.
31. Guissard N, Duchateau J. Neural aspects of muscle stretching. *Exercise and sport sciences reviews.* 2006; 34(4):154-158.
32. Guissard N, Duchateau J. Effect of static stretch training on neural and mechanical properties of the human plantar-flexor muscles. *Muscle & nerve.* 2004; 29(2):248-255.
33. Rhea MR, Ball SD, Phillips WT, Burkett LN. A comparison of linear and daily undulating periodized programs with equated volume and intensity for strength. *The Journal of strength & conditioning research.* 2002; 16(2):250-255.
34. Rhea MR, Alderman BL. A meta-analysis of periodized versus nonperiodized strength and power training programs. *Research quarterly for exercise and sport.* 2004; 75(4):413-422.
35. Williams TD, Tolusso DV, Fedewa MV, Esco MR. Comparison of Periodized and Non-Periodized Resistance Training on Maximal Strength: A Meta-Analysis. *Sports Medicine.* 2017:1-18.
36. Brown LE, Greenwood M. Periodization Essentials and Innovations in Resistance Training Protocols. *Strength & Conditioning Journal.* 2005; 27(4):80-85.
37. Lorenz D, Morrison S. Current concepts in periodization of strength and conditioning for the sports physical therapist. *International journal of sports physical therapy.* 2015; 10(6):734.
38. Pope RP, Herbert RD, Kirwan JD, Graham BJ. A randomized trial of preexercise stretching for prevention of lower-limb injury. *Med Sci Sports Exerc.* 2000; 32(2):271-277.

39. Costa P, Ryan E, Herda T, et al. Acute effects of static stretching on peak torque and the hamstrings-to-quadriceps conventional and functional ratios. *Scand J Med Sci Sports.* 2013; 23(1):38-45.
40. Herda TJ, Costa PB, Walter AA, et al. Effects of two modes of static stretching on muscle strength and stiffness. *Medicine & Science in Sports & Exercise.* 2011; 43(9):1777-1784.
41. Wallmann HW, Christensen SD, Perry C, Hoover DL. THE ACUTE EFFECTS OF VARIOUS TYPES OF STRETCHING STATIC, DYNAMIC, BALLISTIC, AND NO STRETCH OF THE ILIOPSOAS ON 40-YARD SPRINT TIMES IN RECREATIONAL RUNNERS. *International journal of sports physical therapy.* 2012; 7(5):540.
42. Shrier I. Does stretching improve performance?: a systematic and critical review of the literature. *Clinical Journal of sport medicine.* 2004; 14(5):267-273.
43. Morrin N, Redding E. Acute effects of warm-up stretch protocols on balance, vertical jump height, and range of motion in dancers. *J Dance Med Sci.* 2013; 17(1):34-40.
44. Unick J, Kieffer HS, Cheesman W, Feeney A. The acute effects of static and ballistic stretching on vertical jump performance in trained women. *The Journal of Strength & Conditioning Research.* 2005; 19(1):206-212.
45. Critchfield B. Stretching for dancers. *International Association for Dance Medicine and Science www. Dancescience. org. Accessed Nov.* 2012.
46. Letawsky NR, Schneider RG, Pedersen PM, Palmer CJ. Factors influencing the college selection process of student-athletes: Are their factors similar to non-athletes. *College Student Journal.* 2003; 37(4):604-611.
47. Miletić Đ, Katić R, Maleš B. Some anthropologic factors of performance in rhythmic gymnastics novices. *Collegium antropologicum.* 2004; 28(2):727-737.
48. Di Cagno A, Baldari C, Battaglia C, et al. Factors influencing performance of competitive and amateur rhythmic gymnastics—Gender differences. *Journal of Science and Medicine in Sport.* 2009; 12(3):411-416.
49. Behm, Young JD, Whitten JH, et al. Effectiveness of Traditional Strength vs. Power Training on Muscle Strength, Power and Speed with Youth: A Systematic Review and Meta-Analysis. *Frontiers in physiology.* 2017; 8:423.
50. Allison SJ, Bailey DM, Folland JP. Prolonged static stretching does not influence running economy despite changes in neuromuscular function. *Journal of sports sciences.* 2008; 26(14):1489-1495.
51. Babault N, Bazine W, Deley G, Paizis C, Lattier G. Direct relation of acute effects of static stretching on isokinetic torque production with initial flexibility level. *International journal of sports physiology and performance.* 2015; 10(1):117-119.
52. Behm DG, Bradbury EE, Haynes AT, Hodder JN, Leonard AM, Paddock NR. Flexibility is not related to stretch-induced deficits in force or power. *Journal of sports science & medicine.* 2006; 5(1):33.
53. Ogura Y, Miyahara Y, Naito H, Katamoto S, Aoki J. Duration of static stretching influences muscle force production in hamstring muscles. *J Strength Cond Res.* 2007; 21(3):788-792.
54. Freitas SR, Vilarinho D, Vaz JR, Bruno PM, Costa PB, Mil-homens P. Responses to static stretching are dependent on stretch intensity and duration. *Clinical physiology and functional imaging.* 2015; 35(6):478-484.

55. Freitas S, Vaz J, Bruno P, Andrade R, Mil-Homens P. Stretching effects: high-intensity & moderate-duration vs. Low-intensity & long-duration. *International journal of sports medicine.* 2016; 37(03):239-244.
56. Behm DG, Kibele A. Effects of differing intensities of static stretching on jump performance. *European journal of applied physiology.* 2007; 101(5):587-594.
57. Young W, Elias G, Power J. Effects of static stretching volume and intensity on plantar flexor explosive force production and range of motion. *Journal of Sports Medicine and Physical Fitness.* 2006; 46(3):403.
58. Manoel ME, Harris-Love MO, Danoff JV, Miller TA. Acute effects of static, dynamic, and proprioceptive neuromuscular facilitation stretching on muscle power in women. *The Journal of Strength & Conditioning Research.* 2008; 22(5):1528-1534.
59. Beedle B, Rytter SJ, Healy RC, Ward TR. Pretesting static and dynamic stretching does not affect maximal strength. *The Journal of Strength & Conditioning Research.* 2008; 22(6):1838-1843.
60. Bompa T, Buzzichelli C. *Periodization Training for Sports, 3E*, Human kinetics; 2015.
61. Kraemer WJ, Ratamess NA. Fundamentals of resistance training: progression and exercise prescription. *Medicine and science in sports and exercise.* 2004; 36(4):674-688.
62. Aagaard P. Training-induced changes in neural function. *Exercise and sport sciences reviews.* 2003; 31(2):61-67.
63. Prestes J, Frollini AB, de Lima C, et al. Comparison between linear and daily undulating periodized resistance training to increase strength. *The Journal of Strength & Conditioning Research.* 2009; 23(9):2437-2442.
64. Lamas L, Ugrinowitsch C, Rodacki A, et al. Effects of strength and power training on neuromuscular adaptations and jumping movement pattern and performance. *The Journal of Strength & Conditioning Research.* 2012; 26(12):3335-3344.
65. Brenner JS. Overuse injuries, overtraining, and burnout in child and adolescent athletes. *Pediatrics.* 2007; 119(6):1242-1245.
66. Vain A, Kums T. Criteria for preventing overtraining of the musculoskeletal system of gymnasts. *Biology of sport.* 2002; 19(4):329-346.
67. Claessens AL, Lefevre J. Morphological and performance characteristics as drop-out indicators in female gymnasts. *Journal of sports medicine and physical fitness.* 1998; 38(4):305-309.
68. Behm DG, Peach A, Maddigan M, et al. Massage and stretching reduce spinal reflex excitability without affecting twitch contractile properties. *Journal of Electromyography and Kinesiology.* 2013; 23(5):1215-1221.
69. Cramer JT, Housh TJ, Johnson GO, Weir JP, Beck TW, Coburn JW. An acute bout of static stretching does not affect maximal eccentric isokinetic peak torque, the joint angle at peak torque, mean power, electromyography, or mechanomyography. *J Orthop Sports Phys Ther.* 2007; 37(3):130-139.
70. Freitas SR, Mil-Homens P. Effect of 8-week high-intensity stretching training on biceps femoris architecture. *The Journal of Strength & Conditioning Research.* 2015; 29(6):1737-1740.

71. Coxon JP, Stinear JW, Byblow WD. Amplitude of muscle stretch modulates corticomotor gain during passive movement. *Brain research.* 2005; 1031(1):109-117.
72. Avela J, Kyröläinen H, Komi PV. Altered reflex sensitivity after repeated and prolonged passive muscle stretching. *Journal of Applied Physiology.* 1999; 86(4):1283-1291.
73. Gruber M, Linnamo V, Strojnik V, Rantalainen T, Avela J. Excitability at the motoneuron pool and motor cortex is specifically modulated in lengthening compared to isometric contractions. *Journal of neurophysiology.* 2009; 101(4):2030-2040.
74. Reid JC, Greene R, Young JD, Hodgson DD, Blazevich AJ, Behm DG. The effects of different durations of static stretching within a comprehensive warm-up on voluntary and evoked contractile properties. *European journal of applied physiology.* 2018:1-19.
75. Murphy JR, Di Santo MC, Alkanani T, Behm DG. Aerobic activity before and following short-duration static stretching improves range of motion and performance vs. a traditional warm-up. *Applied Physiology, Nutrition, and Metabolism.* 2010; 35(5):679-690.
76. Behm D, Sale D. Velocity specificity of resistance training. *Sports Medicine.* 1993; 15(6):374-388.
77. Gajdosik RL. Passive extensibility of skeletal muscle: review of the literature with clinical implications. *Clinical biomechanics.* 2001; 16(2):87-101.
78. Okamura N, Tsukune M, Kobayashi Y, Fujie MG. A study of viscoelasticity index for evaluating muscle hypotonicity during static stretching. *Engineering in Medicine and Biology Society (EMBC), 2014 36th Annual International Conference of the IEEE*: IEEE; 2014:6919-6922.
79. Akagi R, Takahashi H. Effect of a 5-week static stretching program on hardness of the gastrocnemius muscle. *Scandinavian journal of medicine & science in sports.* 2014; 24(6):950-957.
80. Harvey LA, Byak AJ, Ostrovskaya M, Glinsky J, Katte L, Herbert R. Randomised trial of the effects of four weeks of daily stretch on extensibility of hamstring muscles in people with spinal cord injuries. *Australian Journal of Physiotherapy.* 2003; 49(3):176-181.
81. Kokkonen J, Nelson AG, Eldredge C, Winchester JB. Chronic static stretching improves exercise performance. *Med Sci Sports Exerc.* 2007; 39(10):1825-1831.
82. LaRoche DP, Lussier MV, Roy SJ. Chronic stretching and voluntary muscle force. *The Journal of Strength & Conditioning Research.* 2008; 22(2):589-596.
83. Magnusson S, Simonsen EB, Aagaard P, Boesen J, Johannsen F, Kjaer M. Determinants of musculoskeletal flexibility: viscoelastic properties, cross-sectional area, EMG and stretch tolerance. *Scandinavian journal of medicine & science in sports.* 1997; 7(4):195-202.
84. Magnusson S, Aagard P, Simonsen E, Bojsen-Møller F. A biomechanical evaluation of cyclic and static stretch in human skeletal muscle. *International journal of sports medicine.* 1998; 19(05):310-316.
85. Medeiros DM, Martini TF. Chronic effect of different types of stretching on ankle dorsiflexion range of motion: Systematic review and meta-analysis. *Foot (Edinburgh, Scotland).* 2017; 34:28-35.

86. Magnusson SP, Simonsen E, Aagaard P, Sørensen H, Kjaer M. A mechanism for altered flexibility in human skeletal muscle. *The Journal of Physiology.* 1996; 497(1):291-298.
87. Nakamura M, Ikezoe T, Takeno Y, Ichihashi N. Effects of a 4-week static stretch training program on passive stiffness of human gastrocnemius muscle-tendon unit in vivo. *European journal of applied physiology.* 2012; 112(7):2749-2755.
88. Freitas SR, Mendes B, Le Sant G, Andrade RJ, Nordez A, Milanovic Z. Can chronic stretching change the muscle-tendon mechanical properties? A review. *Scandinavian journal of medicine & science in sports.* 2018; 28(3):794-806.
89. BUCKNER SB, Bacon NT, BISHOP PA. Recovery in Level 7–10 Women's USA Artistic Gymnastics. *International journal of exercise science.* 2017; 10(5):734.
90. Alvar B, Wenner R, Dodd DJ. The effect of daily undulated periodization as compared to linear periodization in strength gains of collegiate athletes. *The Journal of Strength & Conditioning Research.* 2010; 24:1.
91. Lorenz DS, Reiman MP, Walker JC. Periodization: current review and suggested implementation for athletic rehabilitation. *Sports Health.* 2010; 2(6):509-518.
92. Joke K, Nelson Arnold G, Carol E, Winchester Jason B. Chronic static stretching improves exercise performance. *Med Sci Sports Exerc.* 2007; 39(10):1825-1831.
93. de Baranda PS, Ayala F. Chronic flexibility improvement after 12 week of stretching program utilizing the ACSM recommendations: hamstring flexibility. *International Journal of Sports Medicine.* 2010; 31(06):389-396.
94. Ayala F, de Baranda PS, Croix MDS, Santonja F. Comparison of active stretching technique in males with normal and limited hamstring flexibility. *Physical Therapy in Sport.* 2013; 14(2):98-104.
95. Peeler JD, Anderson JE. Reliability limits of the modified Thomas test for assessing rectus femoris muscle flexibility about the knee joint. *Journal of athletic training.* 2008; 43(5):470-476.
96. Davis DS, Quinn RO, Whiteman CT, Williams JD, Young CR. Concurrent validity of four clinical tests used to measure hamstring flexibility. *The Journal of Strength & Conditioning Research.* 2008; 22(2):583-588.
97. Konor MM, Morton S, Eckerson JM, Grindstaff TL. Reliability of three measures of ankle dorsiflexion range of motion. *International journal of sports physical therapy.* 2012; 7(3):279.
98. LaPorta JW, Brown LE, Coburn JW, et al. Effects of different footwear on vertical jump and landing parameters. *The Journal of Strength & Conditioning Research.* 2013; 27(3):733-737.
99. Darmiento A, Galpin AJ, Brown LE. Vertical jump and power. *Strength & Conditioning Journal.* 2012; 34(6):34-43.
100. Brown LE. *Isokinetics in human performance*, Champaing, IL. Human Kinetics; 2000; 97-121.
101. Brown LE, Weir JP. ASEP procedures recommendation I: accurate assessment of muscular strength and power. *J Exerc Physiol Online.* 2001; 4(11):1-21.
102. Watkins CM, Barillas SR, Wong MA, et al. Determination of Vertical Jump as a Measure of Neuromuscular Readiness and Fatigue. *Journal of Strength and Conditioning Research.* 2017.

103. McLeland KA, Ruas CV, Arevalo JA, et al. Comparison of knee extension concentric fatigue between repetition ranges. *Isokinetics and Exercise Science.* 2016; 24(1):33-38.
104. Kataura S, Suzuki S, Matsuo S, et al. Acute effects of the different intensity of static stretching on flexibility and isometric muscle force. *The Journal of Strength & Conditioning Research.* 2017; 31(12):3403-3410.
105. Rhea MR. Determining the magnitude of treatment effects in strength training research through the use of the effect size. *J Strength Cond Res.* 2004; 18(4):918-920.
106. Baker D, Wilson G, Carlyon R. Periodization: The effect on strength of manipulating volume and intensity. *J Strength Cond Res.* 1994; 8(4):235-242.
107. Hoffman JR, Ratamess NA, Klatt M, et al. Comparison between different off-season resistance training programs in Division III American college football players. *The Journal of Strength & Conditioning Research.* 2009; 23(1):11-19.
108. Marshall PW, Cashman A, Cheema BS. A randomized controlled trial for the effect of passive stretching on measures of hamstring extensibility, passive stiffness, strength, and stretch tolerance. *Journal of Science and Medicine in Sport.* 2011; 14(6):535-540.

2.7 Figure and Tables:

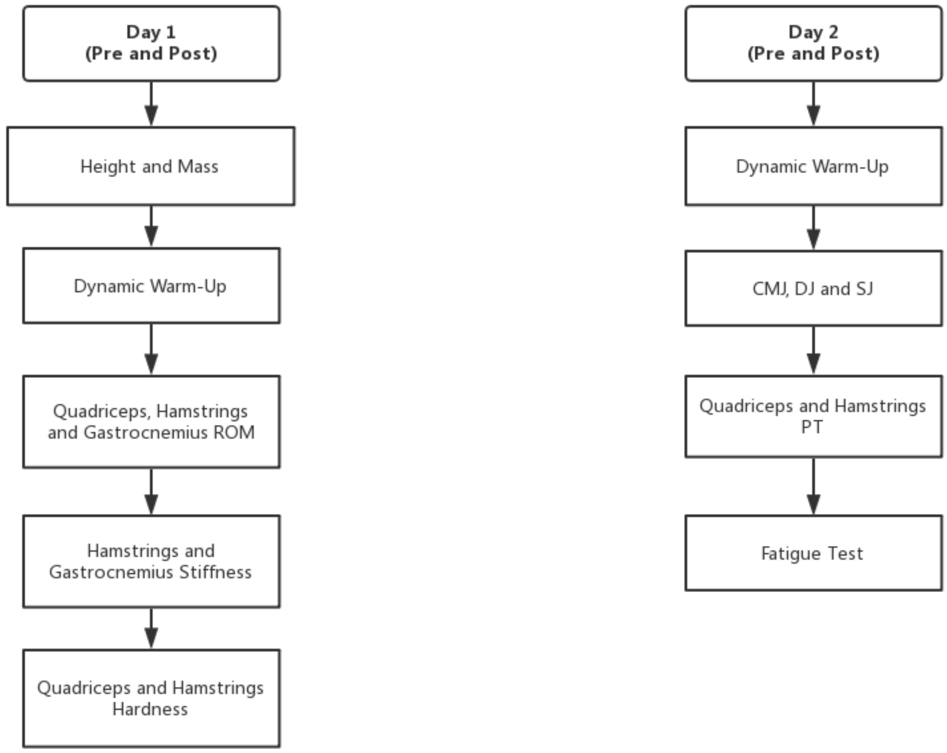

Figure 1: Diagram of testing procedures.

raining Session	Week 1 - 2	Week 3 - 4	Week 5 - 6	Week 7 - 8
Session 1	2 sets at max POD (3 exercises)	2 sets at max POD (6 exercises)	2 sets at max POD (9 exercises)	3 sets at max POD (9 exercises
Session 2	2 sets at max POD (3 exercises)	2 sets at max POD (6 exercises)	2 sets at max POD (9 exercises)	3 sets at max POD (9 exercises
Session 3	2 sets at max POD (3 exercises)	2 sets at max POD (6 exercises)	2 sets at max POD (9 exercises)	3 sets at max POD (9 exercises

Table 1: Linear periodization (LP) stretch training program. POD = point of discomfort.

raining Session	Week 1 - 2	Week 3 - 4	Week 5 - 6	Week 7 - 8
Session 1	2 sets at max POD (9 exercises)	2 sets at max POD (9 exercises)	2 sets at max POD (9 exercises)	2 sets at max POD (9 exercise
Session 2	2 sets at max POD (9 exercises)	2 sets at max POD (9 exercises)	2 sets at max POD (9 exercises)	2 sets at max POD (9 exercise
Session 3	2 sets at max POD (9 exercises)	2 sets at max POD (9 exercises)	2 sets at max POD (9 exercises)	2 sets at max POD (9 exercise

Table 2: No periodization (NP) stretch training program. POD = point of discomfort.

Figure 2: Hamstrings Passive Torque Test.

Stretching Exercises

Figure 3: Sitting Toe Touch on the bench

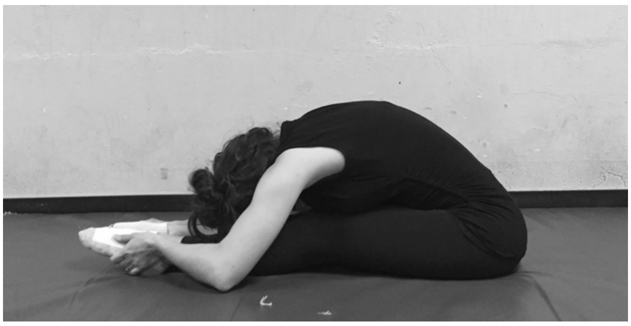

Figure 4: Sitting Toe Touch.

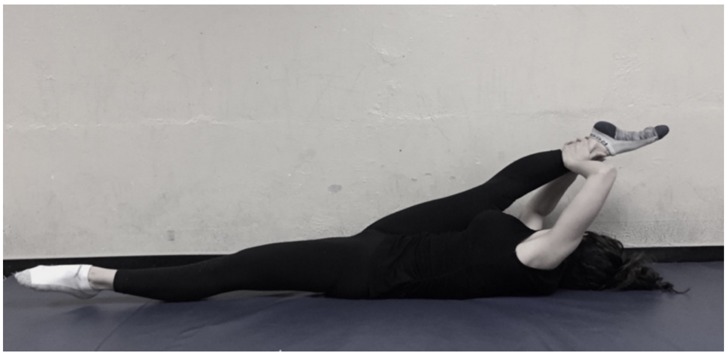

Figure 5: Lying Hamstrings

Figure 6: Hip Flexors

Figure 7: Hip Flexors Kneeling

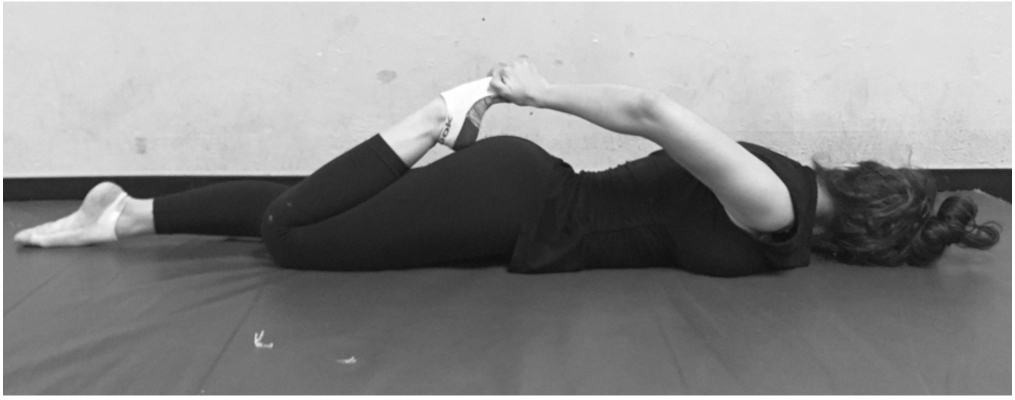

Figure 8: Prone Quadriceps

Figure 9: Pushing the wall

Figure 10: Standing on a bench

Figure 11: Sitting and Pulling.

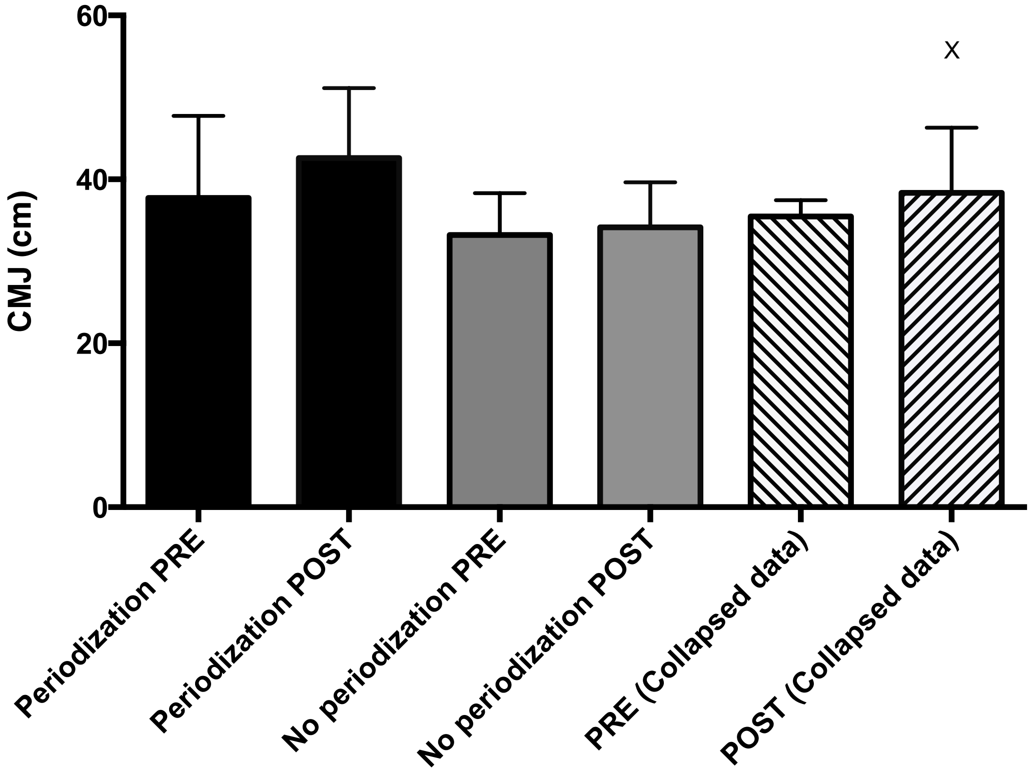

Figure 12: Mean and SD for CMJ height data for pre- to post-training for each group and collapsed (both groups).

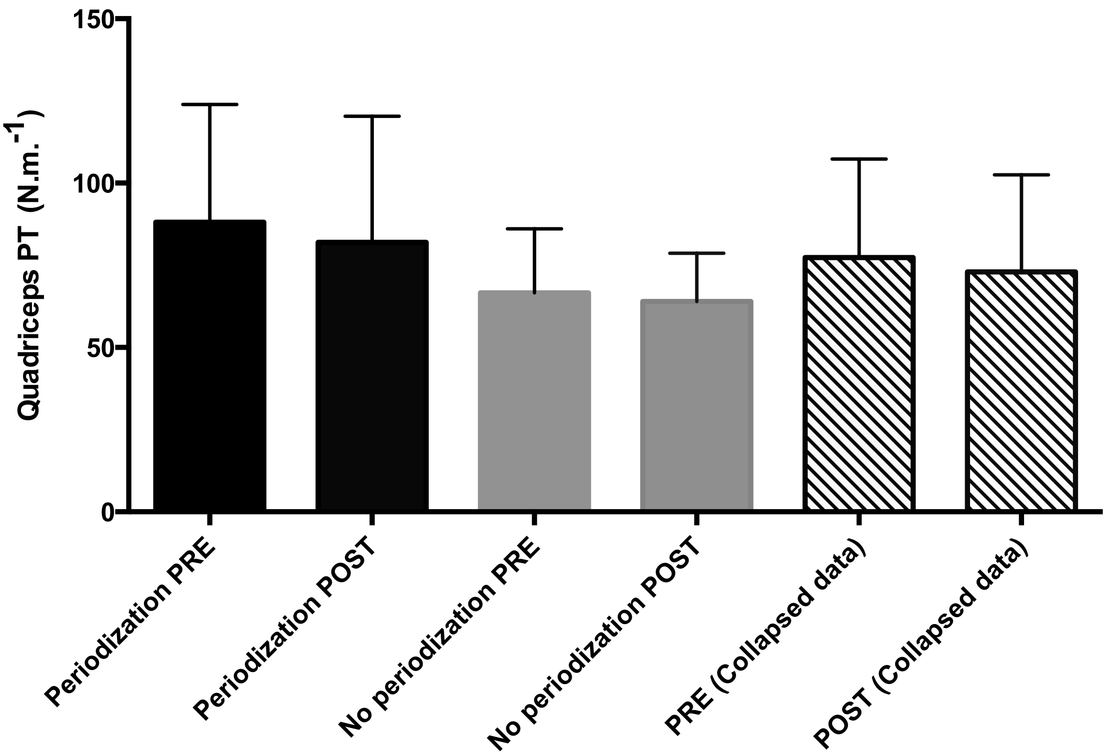

Figure 13: Mean and SD for quadriceps PT data for pre-to-post training for each group. Data collapsed across groups.

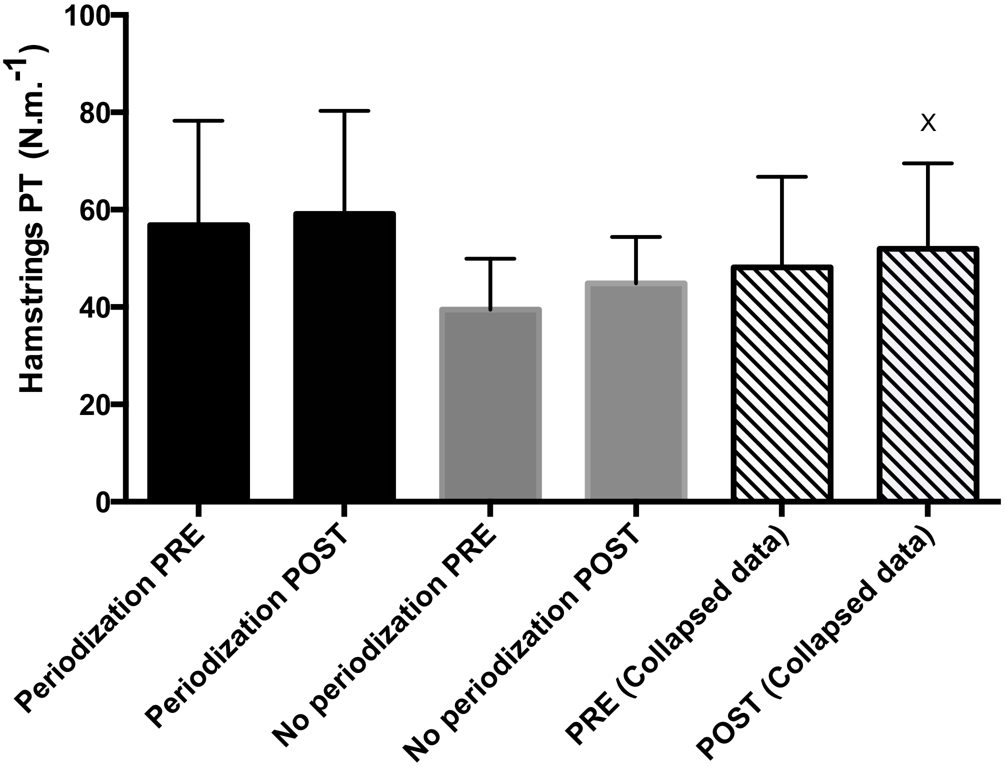

Figure 14: Mean and SD for hamstrings PT data pre-to-post training for each group. Data collapsed across groups.

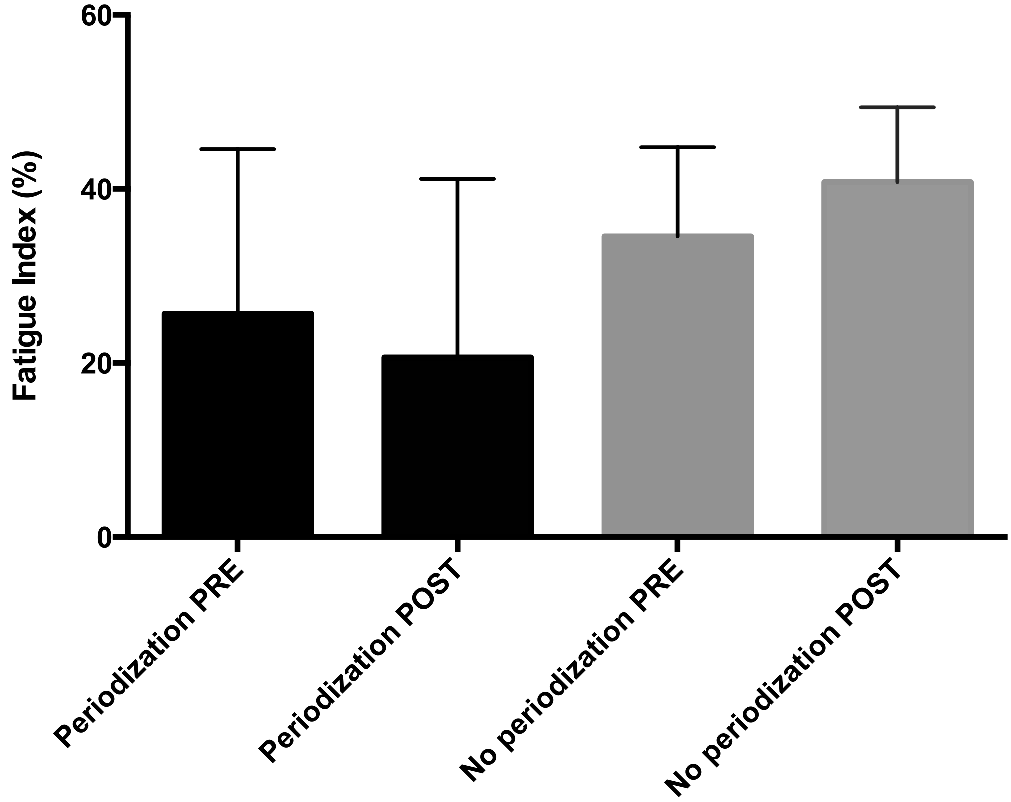

Figure 15: Mean and SD for hamstrings PT data pre-to-post training for each group. Data collapsed across groups.

	No Periodization PRE	No Periodization POST	Periodization PRE	Periodization POST
RF	0.35 ± 0.11	0.44 ± 0.20	0.28 ± 0.05	0.37 ± 0.10
BF	0.05 ± 0.01	0.16 ± 0.19	0.08 ± 0.03	0.09 ± 0.06

Table 3: Mean and SD for RF and BF activity pre- to-post training for each group.

ROM (Degrees)	No Periodization PRE	ES	No Periodization POST	Periodization PRE	ES	Periodization POST	PRE	POST
Hip Flexors	22.66 ± 6.35	0.8 (M)	28.00 ± 5.48	19.75 ± 5.71	>1.0 (L)	28.50 ± 5.71		
Hip Extensors	34.62 ± 12.34	0.4 (S)	39.91 ± 9.18	33.16 ± 4.63	>1.0 (L)	45.00 ± 17.59		
Dorsiflexors	54.29 ± 9.98	>1.0 (L)	65.70 ± 15.26	51.70 ± 14.11	>1.0 (L)	65.54 ± 10.00		
Iaximal Hip Extensors	121 ± 13.68	>1.0 (L)	134. 62 ± 13.42	120.12 ± 9.04	>1.0 (L)	130.37 ± 16.04	120.56 ± 11.21	132.50 ±14.45
Maximal Dorsiflexors	62.37 ± 17.09	0.6 (M)	73.37 ± 9.42	57.75 ± 9.46	>1.0 (L)	68.37 ± 5.04	60.06 ± 13.56	70.87 ± 7.74
Collapsed Hip Flexors							21.20 ± 6.02	28.25 ± 6.55 *
ollapsed Hip Extensors							33.89 ± 9.04	42.45 ± 13.80 *
Collapsed Dorsiflexors							53.00 ± 11.88	65.62 ± 12.47*

Table 4: Mean and SD ROM data pre-to-post training for each group. Data collapsed accross group.

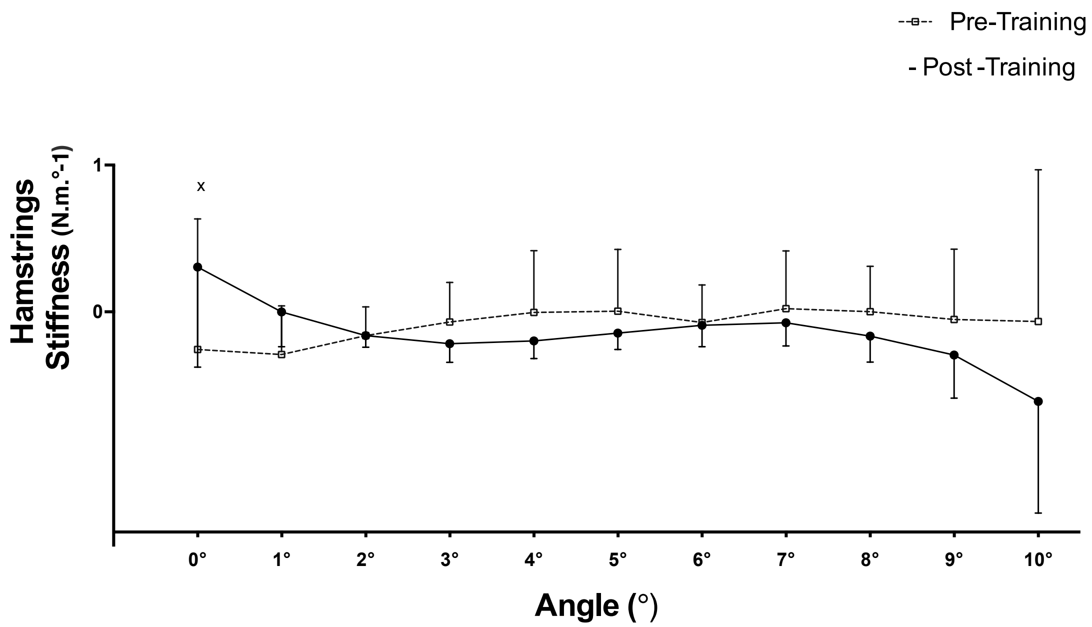

Figure 16: Mean and SD for hamstrings stiffness for both groups for the last ten angles of participants at 80% at max ROM.

Hamstrings Stiffness Angles	0	1	2	3	4	5	6	7	8	9	10
Periodization	0.5 (M)	0.8 (M)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	0.6 (M)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T
No Periodization	0.6 (M)	0.6 (M)	≤ 0.25 (T)	0.5-1.0 (M)	0.5-1.0 (M)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	≥ 1.0 (L)	≥ 1.0 (L)	≥ 1.0 (L)

Table 5: ES for hamstrings stiffness for both groups for each angle of the last tem angles of participans at 80% of max ROM.

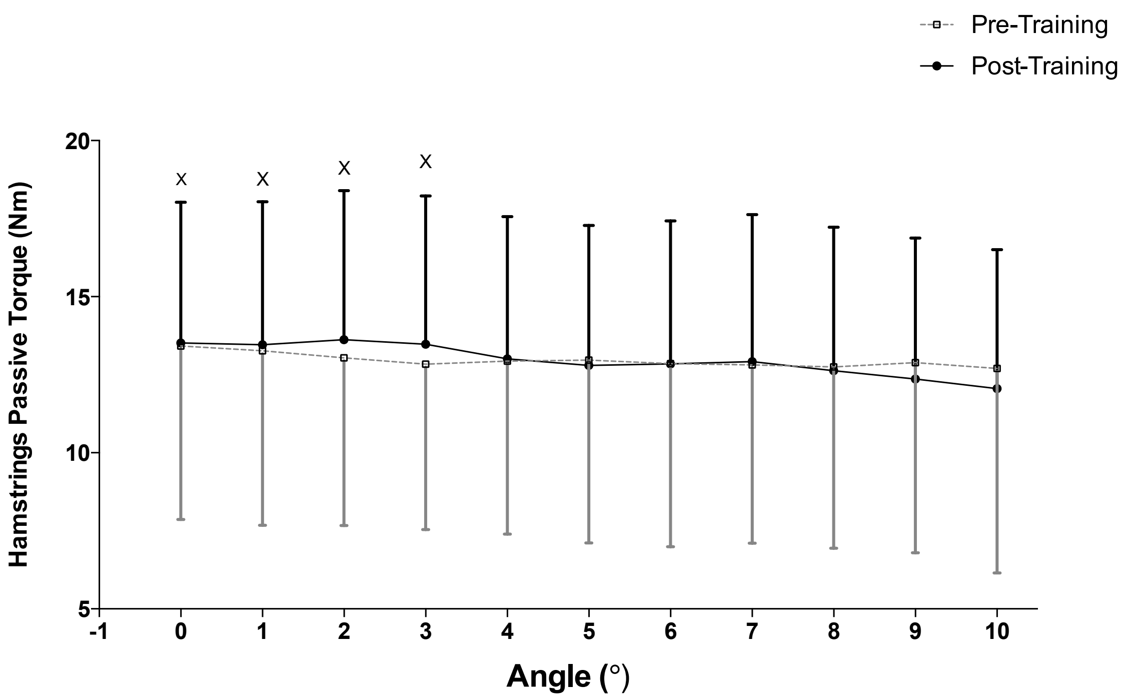

Figure 17: Mean and SD for hamstrings passive torque for each group for the last ten angles of participants at 80% of max ROM.

Hamstrings Passive Torque **Angles**	0	1	2	3	4	5	6	7	8	9	10
Periodization	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	≤0.25 (T)	≤ 0.25 (T
No Periodization	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T)	≤ 0.25 (T

Table 6: ES for hamstrings passive torque for each group and each angle of the last ten angles of participans at 80% of max ROM.